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SOUND PICTURES



A GROUP OF SIX PAPERS
PRESENTED AT THE LAKE PLACID CONFERENCE
OF THE SOCIETY OF MOTION PICTURE ENGINEERS
OUTLINING THE FUNDAMENTAL FACTORS INVOLVED
IN THE PRODUCTION OF SOUND PICTURES

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Sound Pictures

1. The Quality of Speech and Music..... *John C. Steinberg*
2. General Principles of Sound Recording..... *E. C. Wente*
3. Recent Advances in Wax Recording..... *Halsey A. Frederick*
4. Sound Recording with the Light Valve..... *Donald MacKenzie*
5. Synchronization and Speed Control of
Synchronized Sound Pictures..... *H. M. Stoller*
6. Sound Projector System for Use in
Motion Picture Theaters—Part I..... *E. O. Scriven*
Part II..... *H. B. Santee*



THE QUALITY OF SPEECH AND MUSIC

JOHN C. STEINBERG*

IN THE early communication of man, gestures, grimaces and vocal sounds probably played equally important parts. Although all three have survived, the voice has become the one most universally used. With the invention of the telephone and the phonograph it became possible for man to communicate at a distance and to perpetuate his speech. Now man may communicate at a distance and perpetuate, not only his speech, but his grimaces and gestures as well.

This progress has been accompanied by extensive investigations into the physical nature of speech and hearing. It is the aim of the present paper to consider the bearing of various data on the sensory aspects of speech and music. A selected list of published papers that have been consulted is attached.

The organs of speech (Fig. 1) consist of the lungs (not shown in figure), the trachea or windpipe, and the mouth, nose and throat cavities. The larynx is situated at the upper part of the windpipe and contains two muscular ledges known as vocal cords. They are so arranged as to form a straight slit through which the breath passes.

In the process of speaking, the lungs by their bellows-like action force streams of air in and out through the vocal passages. As the streams of air pass through the slit formed by the vocal cords, they are set in vibration so that the slit is alternately opened and closed. A train of sound waves is thus set up in the lower part of the throat. As these waves pass out into the air, certain resonant and transient characteristics are impressed upon them by the vocal cavities and the movements of the tongue, lips, etc. It is these variations which we interpret as speech sounds.

All of the speech sounds except those symbolized by the letters p, k, t, f, s, th (as in thin), ch and sh are produced in this manner. These sounds are called unvoiced sounds and the vocal cords do not enter into their production. They are produced by frictional vibration set up in the mouth itself.

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Both groups may be divided into two classes—those produced by a continuous flow of air which may be called the continuants and those produced by the sudden stoppage of the air which may be called the stops. In the former class are such sounds as a, v, f, etc. In the latter class are such sounds as p, g, d, t, etc.

Although the vocal cords lend quality to the voice they are not highly essential for producing the distinguishing characteristics of the speech sounds. These are produced mainly by the mouth

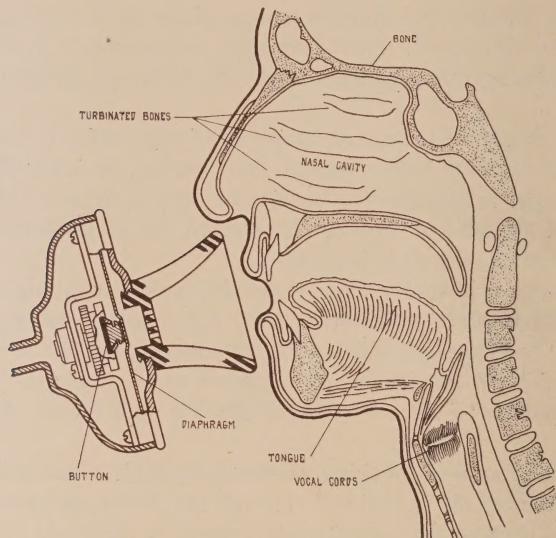


FIG. 1. Cross Section of Head and Vocal Organs.

and nose cavities. This is evidenced by the fact that we can understand whispered speech, in which the vocal cords play no part. As a matter of fact counterparts of the lungs and vocal cords can be located quite outside the body and still produce intelligible speech

A piece of apparatus known as the artificial larynx is a good illustration. An ordinary bellows serves as the lungs, a rubber tube as the windpipe, and a little metal box as the larynx. Inside the box is a reed which vibrates with the passage of air, much like the old style automobile horn. The interrupted air stream is led into the mouth by means of a short pipe which is attached to the metal

box. By properly shaping the mouth the various sounds can be formed.**

This device is used by people who have undergone a surgical operation known as tracheotomy. In this operation the larynx is removed and the windpipe is terminated by a small hole in the patient's neck, through which he breathes. In this case, the bellows is dispensed with, and the rubber tube is fitted over the hole, so that, when he breathes a train of sound waves is produced. In order that he may speak these sound waves are directed into his mouth.

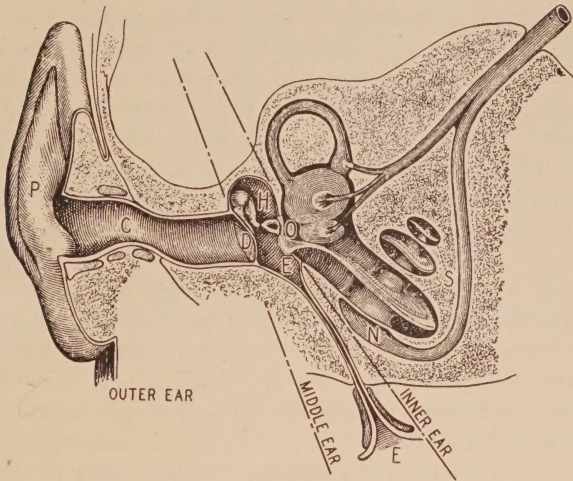


FIG. 2. Cross Section of the right Ear.†

The mechanism of hearing (Fig. 2) is divided into three general parts, the outer ear, the middle ear and the inner ear. The outer ear consists of the external part and the ear canal. The middle ear contains three small bones which are called the hammer, the anvil, and the stirrup. They connect the ear drum with the small window or diaphragm "O" of the inner ear. In the inner ear is located the organ of hearing. It consists of a spiral cavity "S" surrounded by bone. The cavity is filled with liquid. As may be seen from the figure a spiral ledge projects into the cavity. The liquid above this

** The production of the simple speech sounds and also connected speech was demonstrated with the above type of apparatus.

† Reproduced, with permission, from Textbook of Physiology by William H. Howell, M. D., W. B. Saunders Co., Philadelphia.

ledge is separated from the liquid below it by a flexible membrane. The two windows "O" and "E" retain the liquid at the base. At the apex, the membrane is pierced by a small hole so that the liquid may flow from the upper side of the ledge to the lower side. When the window at "O" is pushed in, the window at "E" bulges out and vice versa. The nerves of hearing are distributed along the flexible membrane.

Sound enters the ear as successions of minute condensations and rarefactions of the air, which are known as sound waves. They cause minute increases and decreases in the air pressure near the ear drum. These variations are called sound pressure and cause the ear drum to vibrate. It is supposed that the liquid in the inner ear surges up and down the spiral in accordance with the frequency of vibration. If the frequency is low the pressure is relieved through the flexible membrane near the apex. If the vibration frequency is high, the pressure is relieved near the base. In other words, tones of different frequency disturb the membrane in different positions along its length. This separation enables us to identify the pitch of the tone.

Speech waves are composed of a large number of tones of different vibration frequency which change continually during utterance. These tones cause disturbances which are spread out along the membrane containing the nerves of hearing. The high tones disturb one end of the membrane, the low tones disturb the other end of the membrane. If one could see this membrane it might resemble the keyboard of a player piano in operation. At one instant the keys at one part of the scale are disturbed; at a later instant the keys at some other part of the scale are disturbed. In the case of the ear, the pattern of the disturbance on the membrane is carried to the brain and interpreted as a speech sound.

Fig. 3 shows the range of sound pressure and frequency which the ear can perceive. The vertical axis represents the sound pressure^{††} and the horizontal axis represents frequency of vibration. In the sensation of tone, loudness is caused by the sound pressure and pitch is caused by the frequency of vibration. The lowest pitch that can be sensed as a tone is of an order of 20 cycles, the highest is of an order of 20,000 cycles. The lower curve represents the sound

^{††} The sensation unit is defined as $20 \log P$, where P is the sound pressure.

pressures at which the various pure tones are just audible. It will be noticed that the ear is less sensitive to the low notes, that is, a greater pressure is required for these tones to become audible. The upper curve represents the sound pressures at which the tones cause a sensation of feeling or pain. The faintest tone that can be heard and the loudest tone that can be heard stand in a ratio of one million to one. The ear can detect any tone that falls in the area enclosed by the two curves.

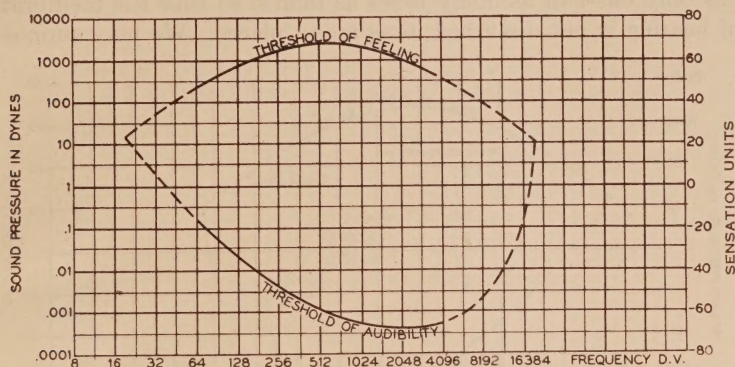


FIG. 3. Auditory Sensation Area.

Studies on the wave forms of speech sounds have shown that the pitch of man's voice is of an order of 128 cycles (vibrations per second), that of woman's voice of an order of 256 cycles. In both cases, overtones of the fundamental chord tone occur in the speech sounds. These studies have shown frequencies as high as 8000 or 9000 cycles in various speech sounds. Studies on the interpretation of speech sounds have also indicated the presence of tones covering a large part of the audible frequency range. This can best be seen by considering the parts of the auditory sensation area which are particularly important to the interpretation of the various speech sounds, as shown in Fig. 4.

Although in the above figure the speech sounds have been grouped in sharply defined areas, it must be understood that actually the sounds overlap these areas somewhat, and that the indicated areas are those which are most important in the interpretation of the sounds. The three voiced consonants which are symbolized by the letters *v*, *z*, *th* (as in *then*), are exceptions and

belong in the unvoiced consonant area. The various speech sounds cover a frequency range up to 8000 cycles, and a sound pressure range of 60 sensation units. The area above 8000 cycles does not contribute appreciably to speech interpretation. It does, however, carry a large part of the sounds of breathing which take place during speech.

In general, woman's speech is more difficult to interpret than man's. This may be due in part to the fact that woman's speech has only one-half as many tones as man's, so that the membrane of hearing is not disturbed in as many places. We may suppose,

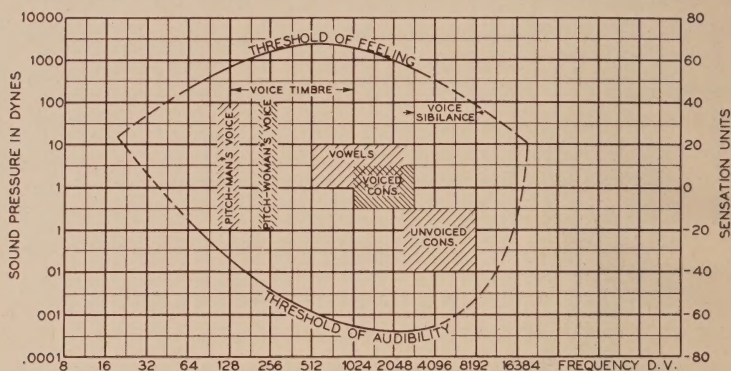


Fig. 4. Useful Area for Speech.

therefore, that the nerve fibres do not carry as much data to the brain for interpretation. The greatest differences occur in the case of the more difficult consonant sounds. In woman's speech these sounds are not only fainter but require a higher frequency range for interpretation. A range from 3000 to 6000 cycles for man's voice corresponds roughly to a range from 5000 to 8000 cycles for woman's voice. Since the ear is less sensitive in the latter range and the sounds are initially fainter, their difficulty of interpretation is greater.

There is one other phenomenon of hearing which enters into interpretation. When sounds containing a number of tones are increased in loudness, the lower tones in the sound deafen the auditor to the higher tones. This deafening or masking effect becomes very marked when the sound pressure of the lower tones is greater than twenty sensation units. In the case of speech, this

effect impairs the interpretation of the higher pitched sounds. The optimum loudness for the interpretation of speech corresponds to a sound pressure between 0 and 20 sensation units. If the sound pressure is less than this, the fainter sounds are inaudible. If the sound pressure is greater, the masking effects impair the interpretation of these sounds.

As in the case of speech, musical sounds consist of a fundamental frequency and various overtones of the fundamental. The tones, however, are sustained for appreciable lengths of time, and when they are changed, the changes usually take place in definite steps, known as musical intervals. The pitch of the tone is determined by the fundamental frequency. This frequency, however, need not be present in the musical tone as the overtones which are multiples of the fundamental may cause the correct pitch sensation.

The frequencies that are present in music depend upon the type of instrument and the character of the music. The composition of musical tones can be obtained by considering the construction of various types of instruments, and by wave form studies.

Musical instruments may be divided into two general classes, string instruments and wind instruments. With strings, the tones may be produced by plucking, striking, or bowing, and are usually reenforced by resonating air cavities and sounding boards. With wind instruments, the tone may be produced with the aid of reeds as in the clarinet, or without reeds as in the flute. In the playing of horns the lips act as reeds.

Each class may be further subdivided into melody and harmony instruments. In the former only one note is usually produced at a time; in the latter several notes are usually produced simultaneously. In general, harmony instruments are capable of producing notes over a much wider frequency range than melody instruments. A given type of instrument of the latter class may, therefore, include several instruments covering different frequency ranges such as the bass, tenor and alto trombone.

Experiments have indicated that notes of different frequency or pitch as produced by a musical instrument, appear about equally loud to the ear. This seems reasonable when we consider that the ear has played an important part in the design of such instruments. Since the sound pressures that are necessary for equality of loudness of various tones are known, it is possible to approximately

determine the range of pressures that are met with in covering the frequency range of music.

In Fig. 5 contour lines of equal loudness are shown for frequencies from 32 to 4000 cycles. The frequency range has been divided into three parts, bass, tenor and alto, and soprano registers, corresponding to the notes produced by various instruments. The contour lines indicate that the notes of the lower registers have greater sound pressures than those of the higher. The range of pressures for various instruments and for various musical notations of loudness are smaller for low notes. Direct measurements of the pressures that are produced by various instruments when played by musicians show this tendency.

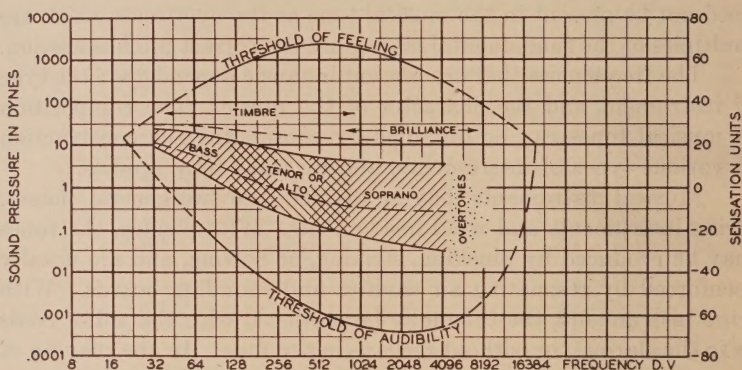


FIG. 5. Useful Area for Music.

The contour lines for loud tones show a smaller change in pressure in going from low to high notes than do the contour lines for faint tones. If instruments are played so that the notes are of approximate equal loudness, an orchestra playing in a resonant room where the sound reaching the players' ears is loud would produce a smaller range of pressures than if it were playing in a very well damped room.

Percussion instruments such as drums and the various accessory traps produce the greatest pressures that are used in music. Although the fundamental frequency of the notes which they emit is fairly low, the notes are particularly rich in tones of higher frequency, which may extend as high as 10,000 cycles. Although these higher tones die out rather rapidly, they are essential to good definition.

The organ, the piano, and the harp have the greatest compass and cover a frequency range from about 16 to 4000 cycles. All three of these instruments are characterized by a rather prominent first overtone, so that their effective range extends as high as 8000 or 9000 cycles.

Owing to their limited compass, the melody instruments are among the easiest to reproduce. In any given register these instruments may be arranged in the following intensity order: wind instruments, and string instruments, the violin producing the faintest sounds. As a class these instruments produce notes covering the frequency range of 32 to 4000 cycles.

From the auditory sensation area, we have seen that the ear is able to perceive a large number of tones which differ in sound pressure and frequency. We have also seen that the voice and various musical instruments produce tones which cover a large portion of the auditory sensation area. In order to obtain information as to the relative importance of various parts of this area to the sensory characteristics of speech and music, experiments have been performed in which the tones falling in various parts have been eliminated from the sounds by means of filters.

When frequencies below 100 cycles, 200 cycles, 300 cycles and on up to 1000 cycles are progressively eliminated from speech, the character of the speech changes markedly. The terms "timbre" or "tone color" best describe the characteristic which is lost. This characteristic appears to be associated with the fundamental and the first few overtones of the voiced sounds and their presence is necessary in order to convey the sensation of timbre. Frequencies below 300 cycles, however, do not appear essential to the correct interpretation of the speech sounds.

When frequencies above 8000 cycles, 7000 cycles, and on down to 3000 cycles are eliminated, the character of the speech again changes markedly. The term "sibilance" appears to best describe the characteristic which is lost. It refers to the prominence of the hissing or frictional character of speech. If attention is directed to such sounds as s, f, th and z, the elimination of frequencies above 6000 or 7000 cycles is readily detectable. It requires rather close attention to detect the elimination of frequencies above 8000 cycles. Elimination of frequencies above 7000 cycles slightly impairs the interpretation of the s and z sounds of woman's voice. Elimination of frequencies above 6000 cycles impairs the interpretation of the

f and th sounds of man's voice, and the interpretation of the f, th, s and z sounds of woman's voice. The impairment due to eliminating higher frequencies is usually greater in the case of female voices.

As in the case of speech the tone color or timbre of musical tones appears to be associated with the fundamental and the first few overtones of the note produced. Timbre is probably more important in music than it is in speech as it is one of the things which distinguish the tones of various instruments. It appears that, in general, the fundamental and the first three or four overtones are necessary in order to distinguish the tones of various instruments. When overtones higher than these are eliminated the tones lose a characteristic which can best be described by the terms "brilliance" or "definition." The tones seem to lose life and become dull. The prominence of these characteristics varies with the type of instrument, the composition of the music and the personality of the musician.

The notes which are used most in music are contained in the octave below middle C and the octave above middle C, that is, from 128 to 512 cycles. The fourth overtone of 512 cycles has a vibration frequency of 8192 cycles, so that tones of this frequency and below occur frequently in music. A trained ear could no doubt detect the elimination of frequencies above this range from the ordinary run of music, but it is probable that the average individual would have difficulty in detecting the elimination of frequencies above even 6000 or 7000 cycles, unless he gave particularly close attention to the percussion instruments.

Owing to the masking effect, the character of both speech and musical sounds changes as the loudness of the sound is increased. The higher notes are masked more and more which has the effect of accentuating the bass notes. The best simulation is obtained therefore when the reproduced sounds are about as loud as the original sounds.

The effects discussed in the above paragraphs were illustrated by means of speech and music reproduced from phonograph records. In recording the compositions, various frequency ranges were removed by means of electrical filters, and different recording levels were used. Hence, the effects could be shown by reproducing the records from an ordinary phonograph.

The records were prepared by Bell Telephone Laboratories and information concerning them can be secured from its Bureau of Publication, 463 West Street, New York City.

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GENERAL PRINCIPLES OF SOUND RECORDING

E. C. WENTE*

THAT sound as perceived by the ear is the result of a disturbance in the air was known to the ancient Greeks, and that objects are set in vibration by intense sounds must have been observed by primitive man, but it was not until 1857, or less than a century ago, that the first instrument was constructed for making a graphical record of sound waves. In that year Léon Scott patented in France an instrument which he called the phonautograph. In Fig. 1 is shown a picture of this instrument. A piece of smoked paper was

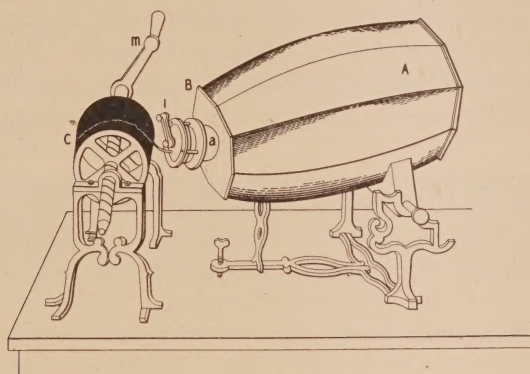


FIG. 1. Scott's Phonautograph.

attached to the cylindrical surface of a drum, which could be rotated by hand and moved forward by a screw. The center of a diaphragm was attached to a stylus through a system of levers in such a manner that the stylus was moved laterally along the surface of the cylinder when the diaphragm vibrated. Over the diaphragm was placed a barrel-shaped mouthpiece. When the drum was rotated, words spoken into the mouthpiece caused the stylus to trace a wavy line upon the smoked paper. This wavy line was the first known record of sound vibrations.

It was twenty years later, in 1877, that Edison brought out an

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epoch-making invention. Edison constructed a machine very similar to the phonautograph but differing in two important details. The smoked paper was replaced by a sheet of tinfoil and the stylus was attached directly to the diaphragm, so that it traced an impression of variable depth when the diaphragm vibrated, instead of a wavy line as in the case of the phonautograph. After such a record had been made the drum was set to the starting point and with the stylus in place was again rotated at the same speed as before. The recorded sound was then intelligibly reproduced. Thus Edison gave us the first phonograph.

In subsequent models the tinfoil was replaced by a wax cylinder. For many years the wax record, either in cylinder or disc form, was used almost exclusively for the recording and reproducing of sound. Although many other methods of recording have been suggested, it is only in the last few years that records made photographically have come into the commercial field as competitors. Both the wax and the photographic records are now being used in conjunction with motion pictures.

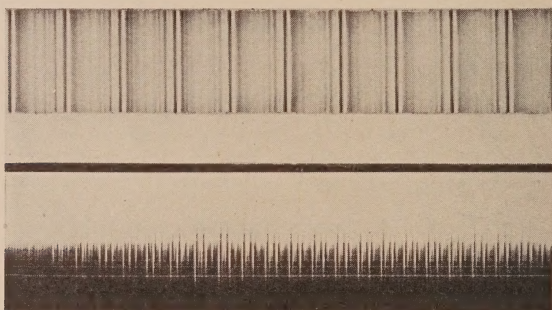


FIG. 2. Types of Photographic Sound Records.

Photographic records are now being made by many different types of apparatus. But they may be divided into two general classes. In one of these classes the record is a trace of constant photographic density but of variable width, while in the other it is a trace of constant width but of variable density. An illustration of each of these is shown in Fig. 2. In one or two proposed methods the record is a combination of both types.

In almost all systems experimented with today there is at least one element which they have in common with the phonautograph, viz.: a diaphragm which is set in vibration by the sound to be recorded. As in the phonautograph the diaphragm may be mechanically connected to the engraving mechanism or recorder; or, again, it may be connected electrically as in most modern systems. But in practically all of them the diaphragm forms an essential element.

Unfortunately a diaphragm does not in general have the same response at all frequencies. A favorite experiment in lectures on elementary physics is to sound a tuning fork and with it, through the air, set in vibration a second tuning fork. In this experiment it is important that the pitch, or the resonant frequency, of the two forks be very nearly the same, otherwise the motion set up in the second fork will be too small to be observable. Diaphragms, and in fact almost any other type of mechanical system, will have at least one resonant frequency, which means that, under the action of sound waves, the response will in general be much greater in this region than at other frequencies.

In the older methods of recording, resonance was purposely introduced in order to obtain records of sufficient amplitude. The frequencies lying in the resonance region were then much over-emphasized. The sound reproduced from such records had a blasting and metallic quality, and well deserved the title "canned music."

Because of the complex nature of speech and music and of the great amount of distortion introduced into the early recorders and reproducers it is not surprising that the quality of reproduction was poor, but it is really astonishing that the reproduced sounds were at all intelligible. In fact, it has been suggested that, had the complex nature of speech sounds been generally known at the time, the invention of the telephone, which preceded the phonograph, might have been delayed for many years since its inventor probably would have dismissed his ideas as altogether impracticable.

Although considerable distortion may permissibly be introduced by the recording and reproducing systems before the character of the sounds is so changed that they can no longer be recognized, it is equally true that, if all classes of sounds are to be reproduced to a degree of fidelity where the ear cannot distinguish them from the original, the amount of distortion must be kept

extremely small. It is therefore necessary to diminish the distortion by the diaphragm to a negligible value.

Primarily that a diaphragm giving a uniform response may be used and that a record of sufficient amplitude may still be obtained, the electrical method of recording has been developed which is today widely used in the production of commercial sound records. In this method the pick-up diaphragm is made a component part of the recording microphone. Here we can content ourselves with a small amplitude of motion and amplify the voltage generated to an amount sufficient for operating a rugged and distortionless recorder. It may be of interest here to compare the amplitude of motion of the diaphragm in the Edison recorder with that of the microphone used in the majority of present recording systems. In the former the maximum amplitude required for the loudest sounds is about 0.001 inch, whereas in the latter under ordinary recording conditions it is only about one-tenth as great and the weight is only one-twentieth as great. It can thus be seen how the problem of design of a pick-up diaphragm is greatly simplified in the electrical method.

It is of course important that the rest of the recording system shall also be free from distortion. However, if a microphone of uniform response is available, the design of a distortionless recorder is made comparatively easy, for its sensitivity may to a large extent be disregarded, inasmuch as the required power can in general be obtained by the use of vacuum tube amplifiers.

In the electrical method, extraordinary improvements have been made over the older systems in the elimination of distortion.

The problem of developing recording apparatus is in many respects identical with that of developing a high quality radio transmitter. In the former, however, there is the additional problem of distortion introduced by the record itself. If, for instance, a record is run at a speed of ten inches per second, and a tone having a frequency of 5000 cycles per second is recorded, the length of one cycle on the record will cover a distance of only 0.002 inch. In the case of wax records the needle must have a very fine point; and in the photographic record the width of the light beam as measured along the direction of motion of the film must be extremely small. At whatever speed the record may be driven, there will always be some frequency beyond which all tones will become more and more attenuated. While the loss of the higher frequencies does not in

general impair the tone quality to the same extent as does the presence of sharp resonance regions, yet it reduces the intelligibility of speech and the richness and brilliancy of musical sounds.

There is another type of distortion commonly present in reproduced sound, which is frequently designated as non-linear distortion. This type of distortion is introduced when the excursion of any element of the system is not proportional to the stimulus. For example, a pure tone, which is of sine wave form, such as is shown in Fig. 3, a, may be reproduced so as to have a wave form similar to that shown in b. Physically, distortion of the wave form in this manner is equivalent to the introduction of extraneous frequencies. If the magnitude of these extraneous frequencies is too great, the tone quality will be very disagreeable. However, a small amount of distortion of this kind is not noticeable, for the

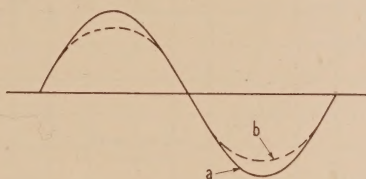


FIG. 3. Non-linear Distortion of a Sine Wave

reason that the primary will mask the extraneous tone. It is a well known fact that a tone must be much more intense to be heard if another tone is sounded simultaneously.

Another type of distortion peculiar to recording is that introduced by a non-uniform speed of the medium on which the record is engraved. This may not always be serious, but, in certain cases of sustained tones, speed variations cause a disagreeable flutter and in some types of music a decided harshness of tone.

One of the most serious problems with which the radio engineer has to contend is static interference. This also has its counterpart in sound reproduction from records. As the ether through which the radio waves are sent is non-homogeneous because of extraneous electrical disturbances, so the sound record is non-homogeneous on account of the non-uniformity of the material on which it is engraved. The noise resulting from these irregularities is often designated as surface noise. In the case of the wax record, an appreciable part of this noise has its origin in the minute irregular-

ities of the material and, in the case of the photographic record, in the finite size of the grains forming the photographic image. The difficulties of eliminating this noise arise from the fact that the physical intensity of audible sounds covers an exceedingly wide range. Fig. 4 shows curves published by Wegel¹ on the sensitivity of the ear. The lower curve gives the threshold of audibility and the upper curve the feeling level, i.e. the level of intensity of sound which becomes painfully loud. The ratio of pressures of the maximum of these curves is about ten million. If a record of this extreme range of volume were to be recorded the amplitude of the loudest

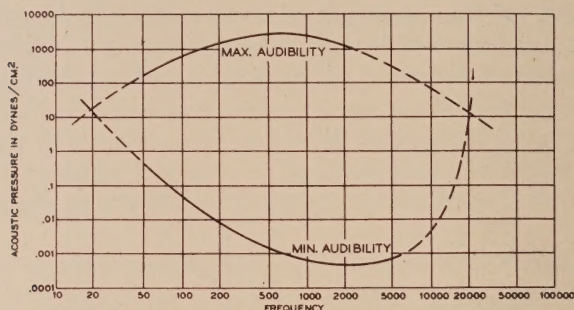


FIG. 4. Sensitivity of the Ear.

tone would have to be ten million times as great as for the faintest tone. There is, in general, a maximum amplitude that a record can accommodate, which, for instance, in the case of the wax record is about 0.002 inch. If a tone having an intensity near the feeling level is recorded at this amplitude, then the amplitude of a tone just audible would be only 0.000,000,000,2 inch. It is difficult to get a material having a degree of homogeneity corresponding to this value. A similar condition obtains in the case of photographic records, where the pattern is formed by grains in the emulsion which have a magnitude somewhat less than 0.001 mm. depending upon the type of emulsion used. The range of volume considered here is extreme. Practically it is not necessary to record a range of this extent, but it serves to illustrate the extraordinary requirements

¹ *The Physical Examination of Hearing and Binaural Aids for the Deaf*, by R. L. Wegel. Proceedings of the National Academy of Sciences, Vol. 8, No. 7, July (1922).

placed upon the recording medium. When the range of frequencies that are to be reproduced is increased the surface noise effect becomes greater. As in the case of the different types of distortion discussed above, the difficulties to be met are increased as the quality of reproduction is improved.

Recent Advances in Wax Recording¹

By **HALSEY A. FREDERICK**

Bell Telephone Laboratories

SYNOPSIS: This paper considers chiefly the frequency-response characteristics and limitations of the lateral cut "wax" record. It shows that the frequency range from 30 to 8,000 cycles can be recorded and reproduced from the record with practically negligible deviation from a flat frequency-response characteristic. The paper brings out the ease with which the record can immediately be replayed from the "wax" as an aid in assisting the artist to obtain the best results. A brief description is given of commercial processing methods including both plating and pressing. These methods give essentially a perfect copy of the original "wax." The time required for this work has been considerably reduced of late so that a test pressing can be obtained within three hours of the cutting of the original "wax."

IN the recording and reproducing of sound by the so-called "electric" method with the "wax" disc, the process may be considered as consisting of eleven steps. In order, these are: (1) studio, with its acoustic conditions, (2) microphone, (3) amplifier, (4) electro-mechanical reorder, (5) "wax" record, (6) copying or reproducing apparatus, (7) hard record or "pressing," (8) electric pickup, (9) amplifier, (10) loud speaker, (11) auditorium.

With this chain of apparatus the chief problem is that of making the reproduced sound in the auditorium a perfect copy of that in the studio. This is a matter of quality or fidelity of reproduction. There are other problems of cost, reliability, time required, etc., which are important but secondary to that of fidelity. While it may be necessary or convenient to introduce distortion in one of these links to compensate for such unavoidable distortion as may occur in other links, experience shows that it is desirable for the sake of simplicity, reliability and flexibility to reduce such corrective warping to a minimum and to make each step in the process as nearly perfect as possible. Perfection of a complete system may be judged by the practical method of listening to the overall result. It is necessary, however, to analyze each element of the complete system. To do this, other more analytical methods of test and standards of performance must be used. One of the most useful of these is the response-frequency curve. In order that all frequencies be reproduced equally and that the ordinary faults of resonance be avoided, this must be flat and free from sharp peaks. Good reproduction requires that frequencies from 50 to 5,000 cycles be included without discrimination. If, however,

¹ Presented before Society of Motion Picture Engineers at Lake Placid, New York, September 26, 1928.

the low frequency range be lowered to 25 or 30 cycles, a noticeable improvement will be obtained with some classes of music, whereas if the upper limit be increased to 8,000 or even 10,000 cycles, the naturalness and smoothness of practically all classes of reproduction will be noticeably improved.

A second important requirement in the judgment or analysis of any such system is that the ratio of output to input shall not vary over the range of currents or loudnesses (as well as frequencies) from the minimum up to the maximum used. If this requirement is not met, sounds or frequencies not present in the original reproduction will be introduced. This type of distortion has probably been heard by all of us in listening to an overloaded vacuum tube amplifier and is often referred to as "non-linear" distortion.

A third requirement not entirely disassociated from the first two is that any shifts in the phase relations shall be proportional to frequency.

Our judgment of the degree of perfection needed in sound reproduction systems is changing and growing more critical, so that what seemed excellent yesterday may be only fair today and tomorrow may seem intolerable. It is therefore necessary that our consideration and analysis be continually more searching and fundamental.

Of the eleven links in the chain of apparatus required for electric "wax" recording and reproduction, only five are peculiar to the "wax" method. These are the electromechanical recorder, "wax" record, the copying apparatus, the "pressing" and the pickup or reproducer. The extent to which the "wax" method is capable of the highest quality of reproduction will be disclosed by an examination of these five links. Any consideration of the practical advantages or disadvantages of the method can logically follow this examination into the quality possibilities.

The consideration which follows refers to the so-called "lateral" cut record; that is, a record in which the groove is of constant depth and oscillates or undulates laterally about a smooth spiral. This is the type used in the Western Electric Company disc record type of synchronized motion picture system. Some, but not all of the considerations and conclusions might apply to the "hill and dale" type record. It is not the purpose of this paper to consider the relative characteristics of "hill and dale" and "lateral" "wax" records.

ELECTROMECHANICAL RECORDER

It is the task of the electromechanical recorder to take power from the amplifier and drive a mechanical recording stylus. The present-

day recorder is a highly developed apparatus based on extensive experimental as well as theoretical studies. A diagrammatic view is given in Fig. 1.² Recorders which have been supplied by the Western Electric Company have been designed to operate over a range of frequencies from 30 to 5,500 cycles. A typical frequency characteristic

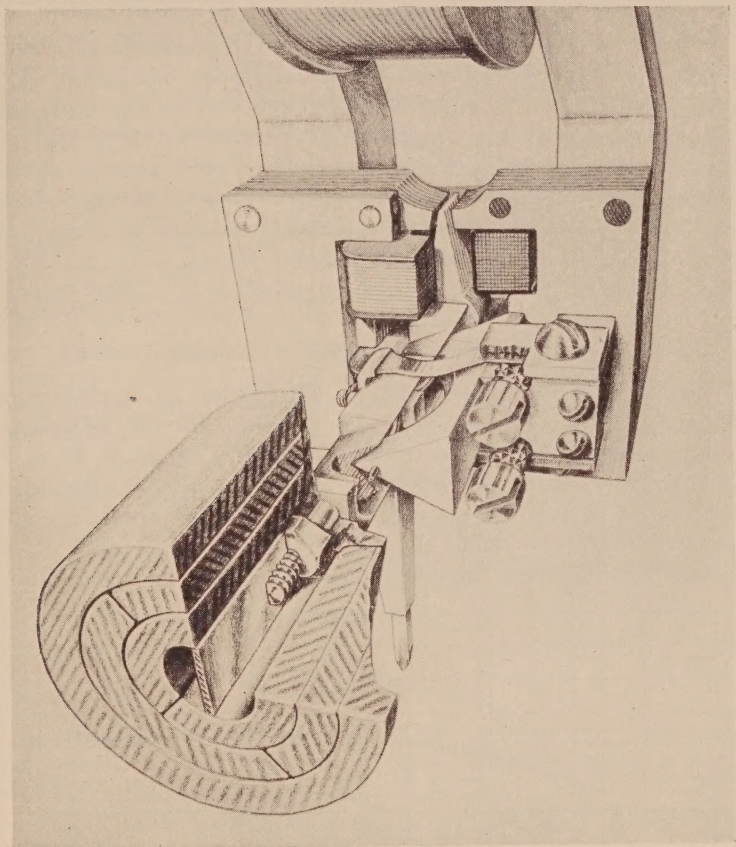


Fig. 1—Diagrammatic view of the electromechanical recorder.

is shown in Fig. 2. The device operates in linear fashion over the range of amplitudes involved in speech and music. As is seen, the response falls off below about 250 cycles. This falling characteristic is necessary in order that the maximum loudness be obtained from a record for a given spacing between grooves without cutting over

² "High Quality Recording and Reproducing of Music and Speech," by J. P. Maxfield and H. C. Harrison, presented at 14th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., Feb., 1926.

from groove to groove. In order that a lateral oscillation in a groove may represent constant intensity of sound or a constant energy over a range of frequencies, not the amplitude of the oscillation but the velocity, which is proportional to the product of the amplitude and the frequency, must be maintained constant. With the characteristic shown with these recorders, constant velocity is obtained from about

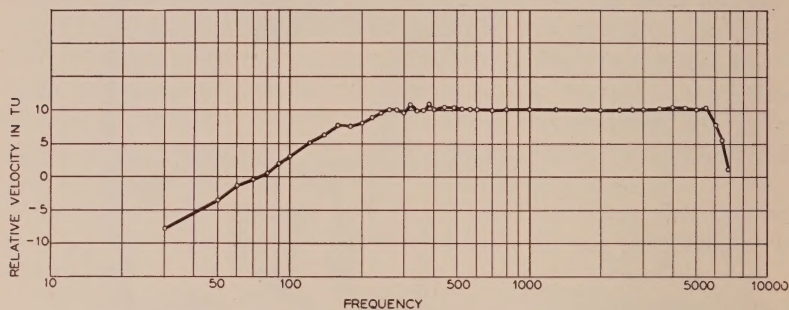


Fig. 2—Typical frequency characteristic of a commercial recorder.

250 cycles to 5,500 cycles. Below 250 cycles an approximately constant amplitude is obtained. If, therefore, sounds of constant absolute intensity are to be recorded over this range of 30 to 250 cycles, there is equal tendency for sounds of the different frequencies in this range to over-cut the record groove. It may be corrected in reproduction by a suitable electric network. Such a network will increase the subsequent amplification required but, as this additional

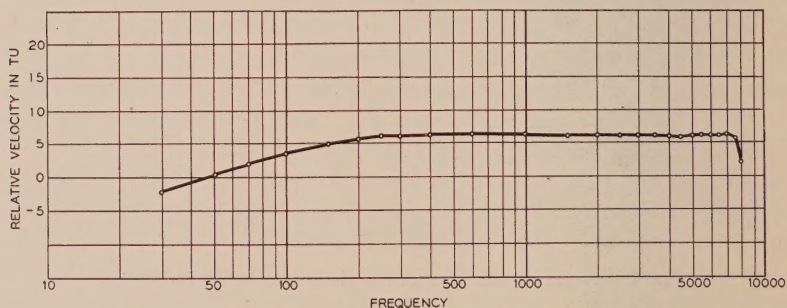


Fig. 3—Frequency characteristic of a laboratory model recorder.

amplification occurs in the first stages, it is not expensive. Practically it has not been found necessary or desirable to introduce such a corrective network since the correction has been largely cared for by the characteristics of the pickups used.

Recent development studies have established the possibility of flattening the response at the low frequency end and of raising the

high frequency cut-off of the recorder. Fig. 3 shows a characteristic obtained with such a laboratory model. This shows uniform performance within ± 1 TU from 250 to 7,500 cycles and within ± 4 TU from 30 to 8,000 cycles. Although its immediate practical value might be limited by other portions of the system, this device is of great interest in that it establishes beyond question the fact that an extremely broad range of frequencies can be successfully recorded in the "wax."

The broad, flat characteristic obtained with electric recorders has been made possible by so designing their elements that they constitute correctly designed transmission systems. In such a transmission system, whether it be an electrical recorder or a long telephone line, a correct terminating impedance is required. The load imposed by the "wax" is somewhat variable but fortunately is rather small. It has been found desirable to make the other impedances in the recorder relatively large so as to dominate the system and thus minimize the effects of any changes in the impedance imposed on the stylus by the "wax." The mechanical load used as a terminating impedance and to control the device has consisted of a rod of gum rubber 25 cm. long. Torsional vibrations are transmitted along this rod. The rate of propagation is about 3,000 centimeters per second so that its length is equivalent to an ideal electrical line of about 1,500 miles. The dissipation along this rubber rod is such that a vibration is substantially dissipated by the time it has travelled down the line and back. It thus constitutes substantially a pure mechanical resistance, the magnitude of this resistance being approximately 2,500 mechanical abohms, referred to the stylus point as its point of application.

"WAX" RECORD ³

In recording the usual procedure is to use a disc from 1 in. to 2 in. thick and from 13 in. to 17 in. in diameter, composed of a metallic soap with small amounts of various addition agents to improve the texture. This is shaved to a highly polished surface on a lathe. This polished disc or so-called "wax" is placed in a recording machine. In Fig. 4 is shown what is essentially a high grade lathe arranged to rotate the "wax" in a horizontal plane at a very uniform speed in a definite relation to the film with which it is synchronized. The recorder with its cutting tool or stylus is moved relative to the surface of the disc, common phonograph procedure being to record from the outer edge of the disc towards the center, whereas in the Western

³ "Some Technical Aspects of the Vitaphone," by P. M. Rainey, presented at the meeting of the Society of Motion Picture Engineers at Norfolk, Va., April, 1927.

Electric Company theater system the direction of cutting is reversed. After a record has been cut into the "wax," the "wax" may be handled and with proper precautions readily shipped from place to place.

The shape of the groove varies somewhat in commercial practice. The groove and stylus most commonly used with Western Electric apparatus are shown in Fig. 5. The groove is approximately .006 in. wide and .0025 in. deep. The pitch of the groove is between .010 in. and .011 in. so that the space between grooves is about .004 in. Thus

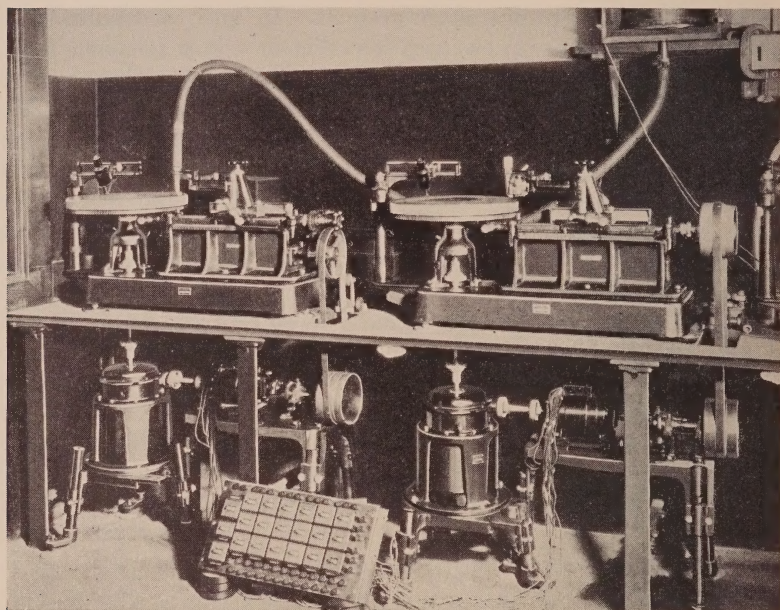


Fig. 4—The recording machine.

the maximum safe amplitude is about .002 in. If this occurs at 250 cycles the corresponding amplitude at 5,000 cycles, assuming constant absolute intensity of sound over this range, would be .0001 in.

It is important that a smooth groove be cut as any roughness in the walls introduces extraneous noise in the reproduced sound. To insure a truly smooth groove the surface of the "wax" must be shaved to a high polish. The texture of the "wax" must be fine and homogeneous which requires not only that the "wax" composition be correct, but that it be operated at the proper temperature. "Waxes" may be obtained commercially which will operate satisfactorily over

the ordinary range of room temperature. The "wax" must be levelled in the recording machine with reasonable care. The stylus must be sharp and so ground that the cut will be very clean. The "wax" shaving is removed as cut by air suction. The operator is aided in maintaining the correct depth of cut by the use of a so-called "advance" ball which rides lightly on the "wax" and serves to maintain uniform depth of cut in spite of small inaccuracies of leveling of the "wax" or deviations from planeness. The "advance" ball is adjusted relative to the stylus by observing the cut with a calibrated microscope. A satisfactory operation of the recording machine requires an ordinarily skilled mechanic with reasonable experience.

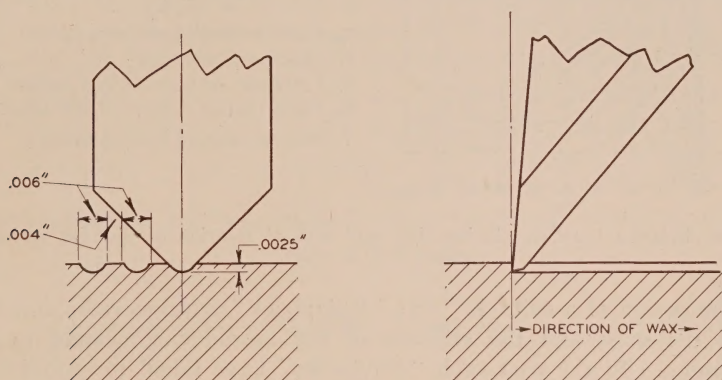


Fig. 5—Recorder stylus.

The rate of rotation is dependent upon the diameter of the record groove which is determined primarily by the length of time which it is desired to have covered by a single disc. The controlling element is the linear speed of the groove past the recorder or reproducer. In the Western Electric system the speed varies from 70 ft. to 140 ft. per minute, in other words, of the same order of magnitude as with the film record. The wave-lengths also are about the same as for a sound record on a film. At the minimum linear speed the half wave-length for a 5,000 cycle wave is .0014 in. If the minimum linear speed is fixed at 70 ft. per minute and the groove spacing is fixed, there is an optimum relation between the size of the record, the rate of rotation and the playing time. This is illustrated graphically in Fig. 6.

After a record has been cut, the sound may be reproduced directly from the "wax" by using a suitable pickup or reproducer. Ordinary reproducers or pickups rest much too heavily on the records to be

used on ordinary "wax." That this would be so is obvious from the fact that the vertical pressures between the point of the needle and the record in an ordinary phonograph are of the order of 50,000 pounds per square inch. Obviously any such pressures would destroy a groove cut in soft "wax." These high pressures have been necessary in order that the groove might properly drive the needle point of the reproducer. Reduction of this pressure requires reduction of the impedance offered by the needle point to transverse vibration.

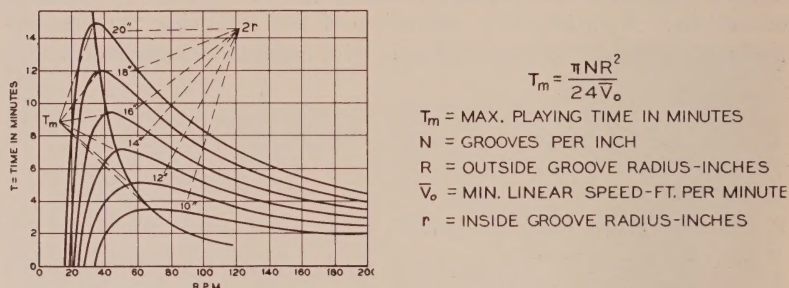


Fig. 6—Relation between playing time and rate of rotation of disc for various values of $R(R = 2r)$.

The design of a suitable "wax" "playback" requires reduction of both the mass and the stiffness of the reproducing system to a minimum. In the past such "playbacks" have failed to reproduce the higher and lower frequencies with much satisfaction. The device shown in Fig. 7 represents a large advance toward ideal reproduction.

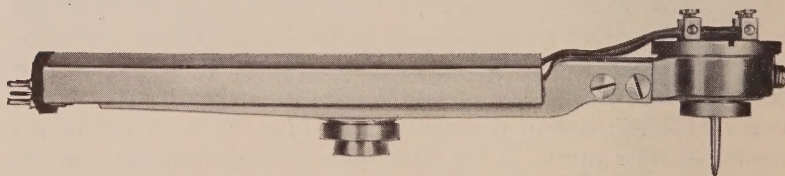


Fig. 7—Playback pickup for "wax" records.

The response of such a device when driven by a "wax" record recorded at constant velocity over the frequency range is shown in Fig. 8. This reproduction is not widely dissimilar from that obtained from finished records with the best electric pickups now commercially available and is sufficiently good to serve as a very valuable criterion in judging the quality of the record. The record may be played a number of times without great injury. The extent of the injury is indicated by the frequency characteristics obtained on successive

playings shown in Fig. 9. They show little change in the low frequency response and a loss of about 2 TU per playing at high frequencies. The practical value in studio work of being able to let an artist immediately hear and criticize the results of his own efforts can hardly be overestimated.

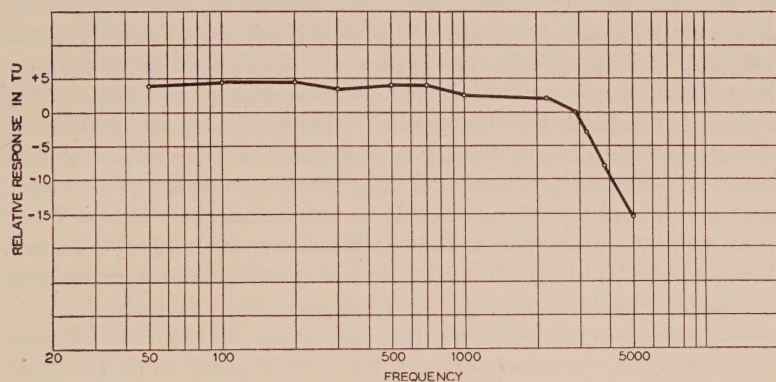


Fig. 8—Response of a "wax playback" driven by constant velocity wax record.

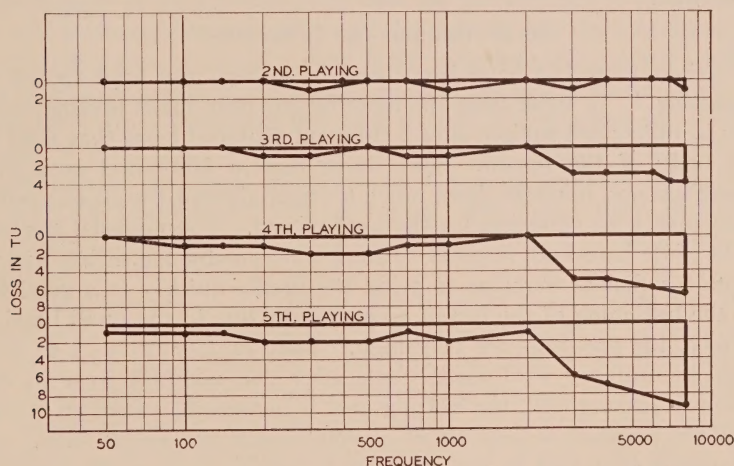


Fig. 9 Loss in response on successive playings of a wax playback driven by constant velocity wax record.

COPYING (PROCESSING) OF THE "WAX" RECORD

After a groove has been satisfactorily cut into the "wax" record, the usual procedure is to render the surface of the "wax" conducting by brushing into it an extremely fine conducting powder. It is then electroplated. The technique in this step varies somewhat with the

different companies doing such work, although not in any fundamental manner. The negative electroplate thus made may be used to hot-press a molding compound such as shellac containing a finely ground filler. This first electroplate is called a "master." From it two test pressings are usually made. If satisfactory the matter is then electroplated with a positive, being first treated so that this positive plate may be easily removed. This positive is sometimes called an "original." From this in turn is plated a metal mold or "stamper." From these, duplicate "originals" may be plated and from them, duplicate "molds" or "stampers." These processes involve no measurable injury to the quality of the record and are comparatively simple and extremely safe in practice. By this practice of making a number of duplicates it is possible to safeguard the "master" and insure against any accident which might destroy a valuable record. From a single "stamper" it is not unusual to make a thousand finished pressings. The time required for these operations is such that test pressings are commonly obtained from the "wax" in 12 hours. Recent refinements in the art have reduced the time required so that finished records may, if necessary, be obtained in 3 hours after delivery of the "wax."

HARD RECORD OR "PRESSING"

Various materials have been used in making the hard record or "pressing." In some cases the material has been made homogeneous and in others the surface is of a different material from that used in the body of the record. Some have used a laminated structure. There has not, however, been much latitude allowed the experimenter concerned with materials for the hard record. The material has had to be quite hard and, in order to show a reasonable life, it has had to contain sufficient abrasive to grind the needle quickly to a good fit. At the beginning of the run of a new needle due to the small bearing surface, the pressures are very high. They rapidly decrease so that with an ordinary loud steel needle after one minute's wear in the ordinary phonograph, the bearing area is increased to such an extent that the pressure is only about 50,000 pounds per square inch. As the needle continues to wear to a larger bearing surface, the pressure obviously continues to decrease. These high pressures and necessary abrasive characteristics of the record have introduced irregularities which are responsible for most of the extraneous noise commonly known as "surface" or "needle scratch."

The "pressing" copies the "wax" record with a very high degree of accuracy so that if our attention be confined to frequency characteristics alone, the "pressing" shows almost complete perfection.

Moreover, it is cheap and durable, and reproduction of the sounds from this record calls for no fine adjustments or intricate apparatus as has been long evidenced by the broad use of the ordinary phonograph.

The major part of the extraneous or "surface" noise found with this method of reproduction comes from the material of the finished record. Recent progress has been made in reducing this noise. As a result of this, together with refinement in the plating processes, records used with Western Electric Company theater equipment during the last two years have shown a reduction of 3 to 6 TU in "surface" noise. This corresponds to eliminating 50 per cent to 75 per cent of that previously present. It is not necessary to reduce the level of "surface" noise to the zero point but merely to the threshold of audibility under the conditions of minimum auditorium noise which are of interest. This noise masks the surface. Moreover, it is not the absolute amplitude of the imperfection giving rise to "surface" noise but the relative magnitude in comparison with the useful sound amplitudes which counts. Thus, an effective reduction in "surface" could be made if we were willing to use larger records or if we were willing to reduce the playing time of the present records by increasing the spacing of the grooves and the amplitude at which the grooves are cut. Any large reduction in "surface" noise made by a reduction in the irregularities in the record material would open the door to increasing the playing time of a record of given size. There is no known absolute or fundamental reason why further improvements in record materials may not be expected to reduce further the amount of "surface" noise. Moreover, large advances in pickup design open distinctly new possibilities as to reductions in "surface."

It has sometimes been thought that in order to reproduce high frequencies properly, the linear record speed would have to be increased or the size of the needle point reduced. At present the diameter of the bearing portion of a representative needle is about .003 in. whereas, as mentioned before, the half wave-length for a 5,000 cycle wave is .0014 in. The factor determining whether a needle will follow the undulation of the groove is not any consideration of the relative diameter of the needle point and the undulation of the groove but rather the radius of curvature of the needle and the bend of the groove. As indicated before, the amplitude at 5,000 cycles would be only about .0001 in. if sounds of that frequency were as intense as those of lower frequencies (.002 in. at 250 cycles). As a matter of fact, sounds of 5,000 cycles or more in speech or music are characterized by lower

intensity than those of lower frequency. If, however, we assume an amplitude of .0001 in. at 5,000 cycles and assume a linear record speed of 70 ft. per minute, then the minimum radius of curvature of the undulation of the groove is .00193 in.⁴ With the foregoing assumption, the radius of curvature of the undulation of the groove becomes equal to that of the needle point at about 7,000 cycles. Taking into account the lower intensities of sounds encountered at these high frequencies, it is obvious that present commercial needle points are quite capable of following the high frequency undulations of the groove up to frequencies of at least 10,000 cycles. The limitations of high frequency reproduction commonly found in the past are associated with limitations in the design of the pickup or reproducer and relate either to inability of the record groove to drive the needle point, with resultant chatter, or inability of the pickup structure to transmit high frequency motions from the needle point to the armature.

ELECTRIC PICKUP

Large advances have been made within the last two or three years in designing electric reproducing structures. The mechanical im-

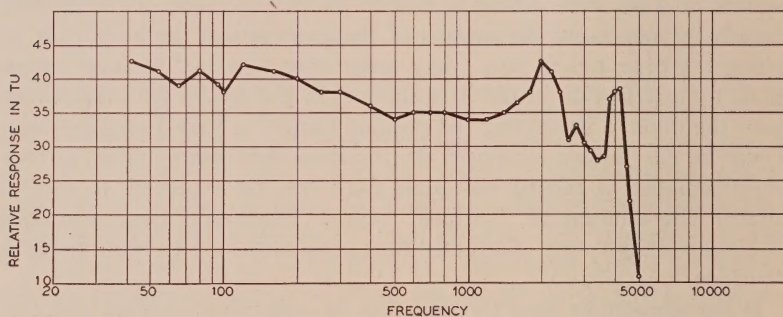


Fig. 10—Response of a 2-a pickup driven by constant velocity pressings.

pedance at the needle point has been reduced so that the needle point truthfully follows the undulations in the groove without necessitating excessive and somewhat destructive bearing pressures. At the

⁴ The minimum radius of curvature is computed by the formula

$$R_c = \frac{V^2}{100\pi^2 A f^2},$$

where:

R_c = minimum radius of curvature in inches.

V = linear speed in feet per minute.

A = amplitude of vibration in inches.

f = frequency in c.p.s.

same time the transmitting structure has been so designed that a very broad range of frequencies is properly transmitted from the needle point to the armature. Moreover, proper mechanical loads have been provided so that the motions after transmission are absorbed and hence not reflected back. This is another way of stating the fact

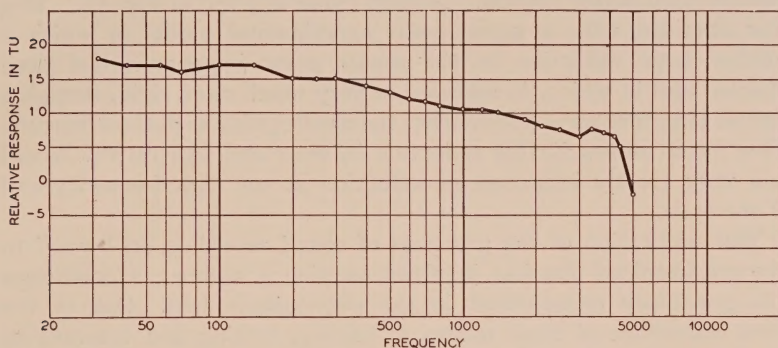


Fig. 11—Response of a 4-a pickup driven by constant velocity pressings.

that resonance as ordinarily considered has been eliminated from these structures.

The curves shown in Figs. 10 to 12 illustrate the steps which have been taken. The pickup shown in Fig. 11 is free from the resonances shown in that of Fig. 10. The resonances present in the earlier

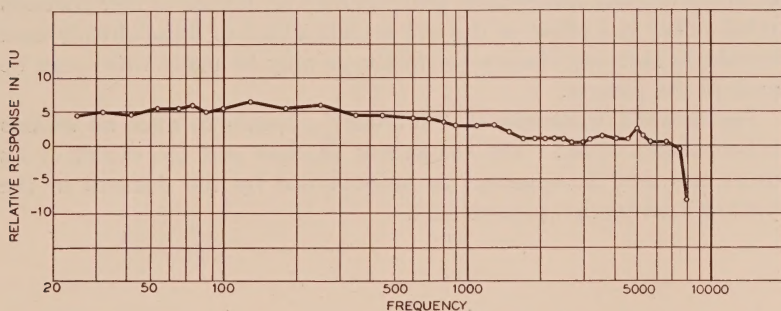


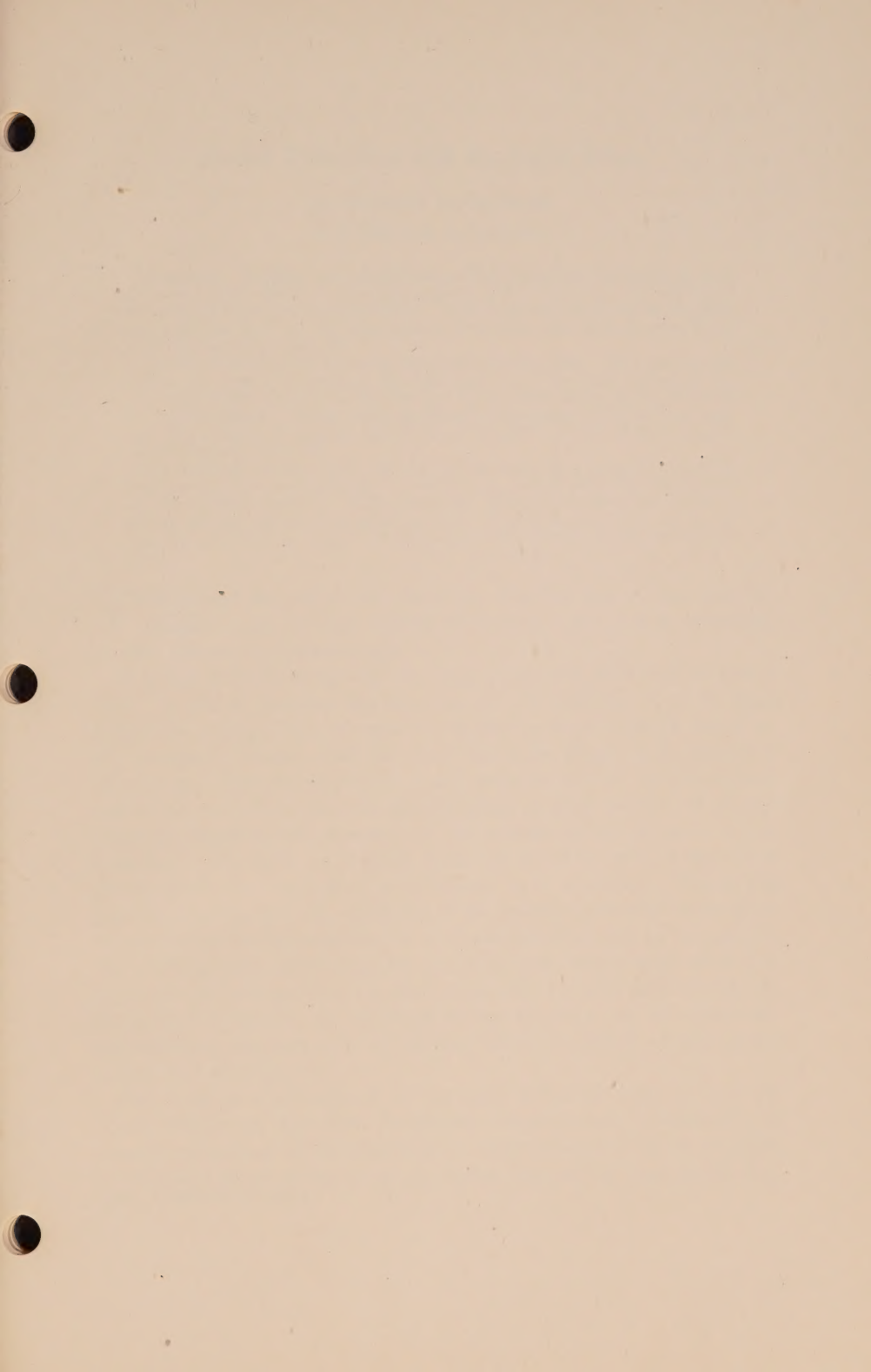
Fig. 12—Response of experimental pickup driven by constant velocity pressings.

pickup involved high needle point impedances in the region of these resonances. These high impedances involved large driving forces destructive both to needle and record. Certain records were injured after only a few playings with this reproducer. The later reproducer is characterized not only by considerably reduced *average* needle point impedance, but, as shown by the curves, the resonance is

practically eliminated and hence there is an even greater reduction from the maximum impedance which occurred in the earlier reproducer at resonance. Both needles and records have a relatively long life with the later type pickup, which has been in commercial use for some months. As is seen, the higher frequencies are reproduced in considerably better fashion. A third curve is given in Fig. 12. This was obtained with a more recent experimental model in which a further large reduction in the needle point impedance had been effected and in which, in addition, a very much more rigid, though a lighter structure served to connect the needle point with the armature. This model shows further reduction in wear and tear on the record and very greatly improved reproduction at the high frequency end of the scale.

The application of the processes of sound recording on "wax" to the synchronized film has involved meeting a number of conditions not previously encountered in the phonograph field. One of the most important of these relates to editing, cutting and rearranging of the picture. Various methods have long been used to copy or "dub" a disc record. The prime requirement is that there be no sacrifice in quality. To attain this end records have sometimes been copied at very low speed. This method appears unnecessarily laborious and slow and the results obtained are not altogether satisfactory in the light of possibilities presented by pickups and recorders of the characteristics shown above. Rearrangement of material on records is entirely practicable, portions may be deleted or new portions added either as a whole or the new sounds added to those already on a record—in fact any changes of this type may be made which can be made in the picture.

The detailed technique of "dubbing" appears to offer no serious technical difficulties. The refinement reached and the extent of its future use may be expected to be governed by the demand in the synchronized motion picture field.



Sound Recording with the Light Valve¹

By DONALD MACKENZIE

Bell Telephone Laboratories

SYNOPSIS: The light valve developed by Bell Telephone Laboratories is an electromagnetic shutter consisting of a loop of duralumin tape formed into a slit at right angles to a magnetic field. Sound currents from the microphone and amplifier flow in this loop causing it to open and close in accordance with the current variations.

The slit is focussed by a lens on the sound negative film. An incandescent ribbon filament is focussed on the light valve, and the light passed by the undisturbed slit appears on the film as a line at right angles to the direction of the film travel. As the valve aperture is modulated by sound currents, the film receives a varying exposure and a sound record of the variable density type is obtained.

For talking pictures such a sound film is made on a separate recording machine synchronized with the camera and is printed alongside the picture on the finished positive. The prints are displaced so that the sound is advanced over the corresponding picture. This is in order that the sound may be projected at a point of continuous film motion below the picture gate.

THE sound records I am about to describe are of the variable density type, and the method of making them is that developed by Bell Telephone Laboratories.

It is not difficult to specify the requirements of this type of sound film. So far as possible the exposure of the negative must be kept within the straight line portion of the Hurter and Driffeld curve for the emulsion chosen, and the print must be timed with the same restriction. The development of the negative and of the print must result in a positive where the transmission of each element of length is proportional to the exposure of the corresponding element of the negative. The light modulator must be supplied with undistorted power from the recording microphone and amplifier. When the positive is projected, the striations of the sound track must be enabled to modulate the illumination of a photo-sensitive cell to retranslate the photographic effect into electrical current which shall be a fair copy of the microphone current generated by the original sound. From this point on the problem is the familiar one of sound reinforcement, the film and cell having taken the places of the sound source and microphone.

Fig. 1 shows a photograph of the light valve, invented in 1922 by E. C. Wente of the Bell Telephone Laboratories. Essentially, it consists of a loop of duralumin tape suspended in a plane at right

¹ Presented before Society of Motion Picture Engineers at Lake Placid, New York, September 25, 1928.

angles to a magnetic field. The tape, 6 mils wide and 0.3 mil thick, is secured to windlasses *A* and *A'* and stretched tight by the spring held pulley *B*. At points *C* and *C'* insulated pincers confine the central portions of the tape between windlasses and pulley to form a slit 2 mils wide. Supporting this loop and adjusting devices is a slab of metal with central elevation *D*, which constitutes the armature of an electromagnet. The central portions of the loop are supported on insulating bridges to lie 3 mils above the face of *D*; here the sides of the loop are centered over a tapered slot, 8 mils wide by 256 mils long in this plane, opening to 204 mils by 256 mils at the outside face of the armature. Viewed against the light, the valve appears as a slit 2 mils by 256 mils.

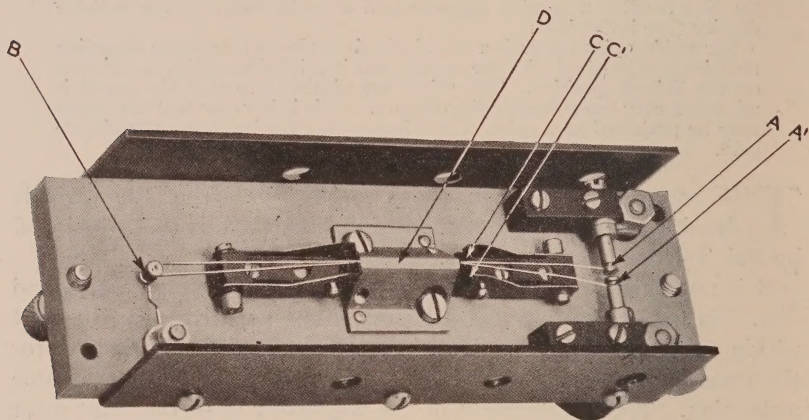


Fig. 1—The light valve.

The electromagnet core has a similar elevation opposing *D* across an air gap of 8 mils which closes to 7 mils when the magnet is energized from a 12 volt battery. A tapered slot in the magnet core begins 8 mils wide by 256 mils long and opens with the same taper as the slot in the armature. When the assembly of magnet and armature is complete, the valve constitutes a slit 2 mils by 256 mils, its sides lying in a plane at right angles to the lines of force and approximately centered in the air gap. The windlasses *A* and *A'*, one of which is grounded, are connected to the output terminals of the recording amplifier. If the magnet is energized and the amplifier supplies a sine wave current from an oscillator, the duralumin loop opens and closes in accordance with the current alternations.

When one side of the wave opens the valve to 4 mils and the other side closes it completely, full modulation of the aperture is accom-

plished. The natural frequency of the valve is set by adjusting the tension applied by the pulley *B*; for reasons which involve many considerations the valve is tuned to 7,000 cycles per second. Under these circumstances about 10 milliwatts of A.C. power are required for full modulation at a frequency remote from resonance; about one one-hundredth of this power at the resonant frequency. The impedance of the valve with protecting fuse is about 12 ohms.

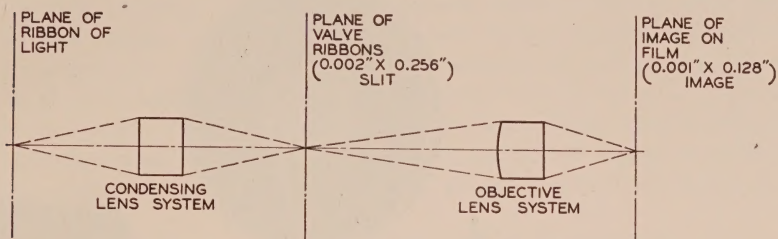


Fig. 2—Diagram of the optical system for studio recording.

If this appliance is interposed between a light source and a photographic film we have a camera shutter of unconventional design. Fig. 2 shows a diagram of the optical system for studio recording. At the left is a light source, a ribbon filament 18 ampere projection lamp, which is focussed on the plane of the valve. The light passed by the valve is then focussed with a 2 to 1 reduction on the photographic film at the right. A simple achromat is used to form the image of the filament at the valve plane, but a more complicated lens, designed to exacting specifications by Bausch and Lomb, is required for focussing the valve on the film. The undisturbed valve opening appears on the film as a line 1 mil by 128 mils, its length at right angles to the direction of film travel. The width of this line varies with the sound currents supplied to the valve, so that the film receives a varying exposure: light of fixed specific intensity through a varying slit.

Fig. 3 shows a studio recording machine with the door of the exposure chamber open. In this machine the film travels at 90 feet per minute, and the sound track is made at the edge away from the observer. The line of light, the image of the valve, overruns the perforations by 6 mils, extending toward the center of the film 122 mils inside the perforation line. The right-hand sprocket serves to draw film from the feed magazine above and to feed it to the take-up magazine below; this sprocket is driven from the motor shaft through a worm and worm-wheel. The left-hand sprocket engages 20 perforations and is driven through a mechanical filter from a worm and worm-wheel

similar to that driving the feed sprocket. The mechanical filter enforces uniform angular velocity of the left-hand sprocket which carries the film past the line of exposure: the focussed image of the valve; balancing of the flywheel which forms part of this mechanical filter holds the angular velocity constant to one-tenth of one per cent, despite the imperfections of the driving gears.

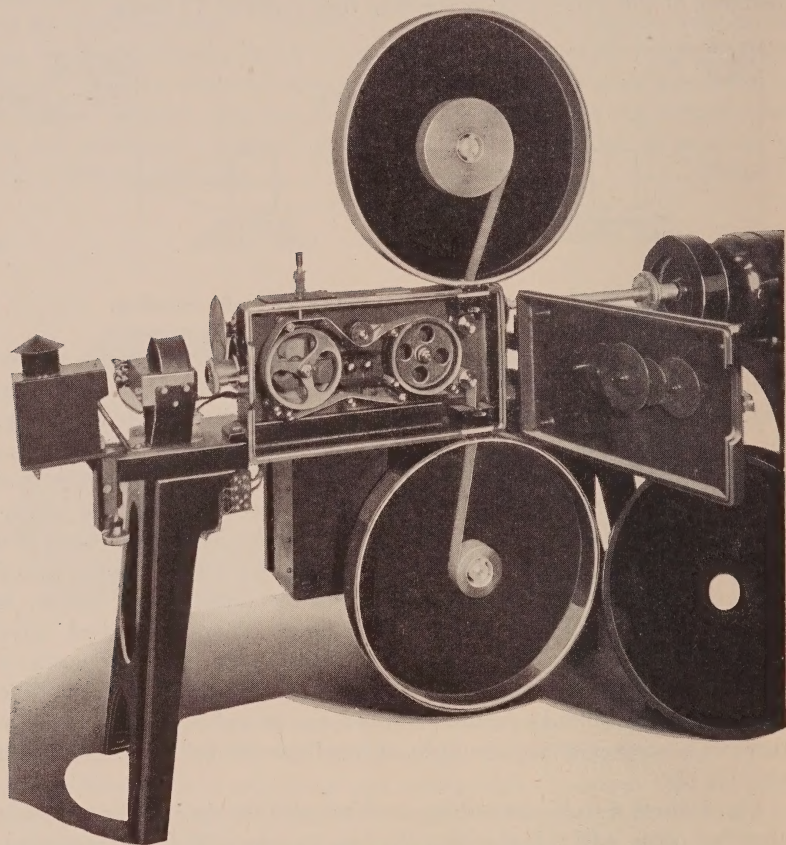


Fig. 3—Studio recording machine.

So far we have provided a means for driving the film and a means for modulating the light thereon, but we have not chosen the average illumination about which the modulation is to take place. The maximum exposure corresponds to the maximum opening of the valve and is therefore double the average.

Choose now the contrast to which the negative sound record is to

be developed and draw the Hurter and Driffeld curve for this contrast for the emulsion chosen for the negative sound record. The maximum exposure should correspond to the beginning of over-exposure, the average should be half this. The Hurter and Driffeld curve will give the density of the over-exposure point for the chosen contrast and the density for half this exposure. Let the machine be run to expose film to light through the unmodulated valve for several values of the lamp current. Develop the film and measure the densities due to the various values of lamp current. Select, by interpolation if necessary, the lamp current which corresponds to half over-exposure. With this current in the lamp the machine is ready to make a sound record, since the focussing of the valve has already been done and manufacturing specifications insure that the line of illumination shall lie, within 3 minutes of arc, at right angles to the direction of film travel.

Consider at this point the procedure in the recording studio. Adding sound to the picture introduces no complication of technique other than to require sufficient rehearsing to make sure of satisfactory pick-up of the sound: microphone placement must be established and amplifiers adjusted to feed the light valve currents which just drive it to the edge of overload in the fortissimo passages of music or the loudest utterances of speakers.

In Fig. 3 the photograph shows a photoelectric cell mounted inside the left-hand sprocket, which carries the film past the line of exposure. Fresh film transmits some 4 per cent of the light falling on it, and modulation of this light during the record is appreciated by the cell inside the sprocket. This cell is connected to a preliminary amplifier mounted below the exposure chamber, and with suitable further amplification the operator may hear from the loud speaker the record as it is actually being shot on the film. Full modulation of the valve implies complete closing of the slit by one side of the wave of current; this modulation should not be exceeded or photographic overload will abound.

One or more cameras and one or more sound recording machines are driven by motors electrically synchronized from a common distributor. Speed control and synchronization of these motors are described in Mr. Stoller's paper. At the beginning of the day's work a check is made of the operation of the driving motors, and the tuning-and-spacing of the valves is verified.

Fig. 4 is a schematic diagram of the studio equipment for sound recording. Provision is made for combining if desired the contributions of several microphones on the set. This combination is

under the control of the mixer operator in the monitoring room, viewing the set through a double window in the studio wall. The mixer controls also the gain of the amplifiers for the recording machines.

The diagram shows relays which permit the mixer to connect the horn circuit either directly to the recording amplifier or to one or the other of the monitoring photoelectric cells in the film recorders. The direct connection is used in preparing the sound pick-up in the studio: the program is rehearsed until satisfactory arrangement of microphones and of amplifier gain is effected. The electrical charac-

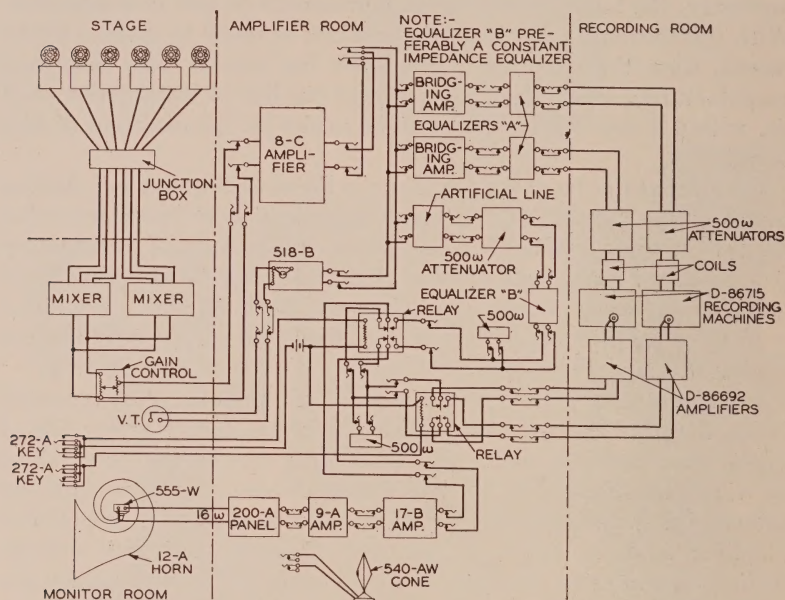


Fig. 4—Schematic diagram of the studio equipment for sound recording.

teristic of this direct monitoring circuit is so designed that the sound quality heard in the horns shall be the same as the quality to be expected in the reproduction of the positive print in the theater. Acoustic treatment of the walls of the monitoring room secures the reverberation characteristic of the theater, and the monitoring level is so adjusted that the mixer operator hears the same loudness that he would wish to hear from the theater horns. It is capitally important that the operator judge his pick-up on the basis of sound closely identical in loudness and quality with that to be heard later in theater reproduction.

After the pick-up has been established on the direct monitoring

circuit, the output of the recording amplifier is applied to the light valves and the monitoring horns are connected to the photo cell amplifiers on the recording machines. With no film in the machine and at a convenient lamp current a complete rehearsal is made to verify the operation of the valves at the proper level. Film is then loaded, cameras and sound recorders are interlocked and starting marks made on all films by punches or light flashes.

A light signal from the recording room warns the studio, which after lighting up signals back its readiness to start. The machine operator starts the cameras and sound recorders, brings up the lamp current to the proper value, and when the machines are up to speed signals the studio to start. During the recording, the mixer operator monitors the record through the light valves, thereby assuring himself that no record is lost.

In the choice of emulsion for the sound negative, the usual designation of speed may be disregarded, because it is desired to make the exposure of the unmodulated track many times the under-exposure of the emulsion used. The advantages of positive emulsion for the sound negative have come to be generally recognized; positive has been used by Bell Telephone Laboratories since 1924. The scale of Eastman positive film is about 20 to 1; we adjust the recording lamp current to give an illumination on the film for the unmodulated track of 10 times the under-exposure. After one lamp has been calibrated as described before it may be replaced when necessary by another in which the wattage in the ribbon filament is the same; the light emission is very closely correlated with the wattage. Where the unmodulated or average exposure is ten times the under-exposure minimum, 90 per cent modulation of the light can be permitted without running into under-exposure on the faint side of the wave. For sound currents reaching 100 per cent modulation of the light, 90 per cent of the wave is free from distortion; if the average light were halved, still 80 per cent would be free from distortion. There is therefore considerable latitude in the average exposure, and the negative is satisfactory if the transmission of the unmodulated track lies between fairly wide limits.

The choice of the negative sound gamma is determined by the practice of the laboratory in regard to picture development. It is usual to see on the screen pictures whose overall gamma considerably exceeds unity. On the sound track the overall gamma should equal unity, and the development of sound negatives should be uniform, though that of picture negatives is left to the judgment of the finisher.

Theoretically, it should be immaterial what combination of reciprocal values is chosen for the negative and positive sound gammas. Prac-

tically, we have to recognize the existence of ground noise in all records and take precaution to minimize it. No matter how excellently we reproduce the fortissimo passages, our record is unsatisfactory unless the ground noise is low enough for a wide volume range, that is, a wide range in level between fortissimo and pianissimo. Whether our negative sound record is made on negative or positive emulsion, there is always the danger that in reproduction we shall encounter variations in transmission from point to point due to local variations in the celluloid base, to local action of the developing agent, or to a developer excessively granular in action. The photoelectric cell is able to recognize variations of $1/10$ of 1 per cent, whereas the eye ignores contrasts under 2 per cent. These local variations in transmission, continued to the positive print, constitute the ground noise.

The remedy is, in part, to choose a developer as little granular in its effect as possible. In part, to insist on machine development of the sound film with thoroughly agitated developer. Further, to carry the sound development to a high gamma; this obviates to a large extent flow marks of the developer, and goes a long way to escape local variations in the base by developing the negative striations to be conspicuous in comparison.

In 1924 we concluded that the optimum choice was positive emulsion developed to unit gamma for both sound negative and sound print. This is feasible for sound records separate from pictures, but a compromise must be made for the combination of sound and picture in a single positive print. Here the positive development required for a satisfactory picture is always to a gamma far above unity.

It is customary to develop picture negatives by inspection, having in mind the uniform positive development to be undergone by the prints from these negatives. The gamma of these positives need never exceed 1.8; the sound negative then should be developed to 0.55. In order not to disturb the practice of the film laboratory, we ask that the positive development be standardized and its gamma ascertained, the reciprocal of this gamma then arranged for in the standardized negative development. A negative gamma above 0.5, together with the precautions of careful handling, permits the realization of an adequate volume range.

It is beyond the scope of this paper to discuss the details of manipulation and of choice of developer, but I wish to acknowledge the cooperation of Mr. J. W. Coffman in the solution of such problems. The problem is the reduction of ground noise, and its seriousness is not to be diminished by choosing a different recording method.

In printing the sound negative, a uniform density for the print of the unmodulated track is desired. The volume of reproduced sound

for a given reproducing light source, varies directly with the average transmission and the per cent modulation of this average. This average density should be on the straight line portion of the positive Hurter and Driffield curve, far enough to keep the denser negative portions from reaching the under-exposure region. For Eastman positive film a suitable transmission of the unmodulated portion of the sound print is 35 per cent, referred to air, for the usual values of positive gamma: 1.4 to 1.8. At this average transmission only the peaks of the recorded sound will encroach on the region of under-exposure. For the reciprocally developed negative track the region of under-exposure will have been reached by occasional peaks on the other side of the wave, and such photographic distortion as exists will be balanced between positive and negative.

Here we appropriately consider the photographic distortion as it occurs in variable density records. If the entire negative exposure has been confined to the under-exposure region of the emulsion chosen, a huskiness will result in the reproduction which can not be corrected by any known technique. But if the unmodulated negative transmission, for a gamma of 0.55, is about 16 per cent referred to air, 90 per cent of the wave will be clear of under-exposure, and experience shows that the ear detects no distortion. In telephonic terms, everything at a level 1 TU below full modulation will be free from distortion, and the peaks will be substantially perfect. The same may be said of the positive printed to an average transmission of 35 per cent, provided the overall gamma approximates unity.

It has been calculated that if the overall gamma departs from unity by 0.2 in either direction, a harmonic of 5 per cent amplitude of the fundamental will be introduced. Experimentation has shown that a 5 per cent harmonic is the least detectible. We state then the tolerance on the overall gamma for the sound track as 0.8 to 1.2. Variation of corresponding amount in the contrast of a picture print is intolerable; therefore greater latitude in contrast is permissible in the sound record than could be tolerated in the accompanying picture.

In printing these sound negatives in combination with pictures for projection in the theater, it is customary at the present time to print one negative, masking the space needed for the other, then run the positive again through the printer with the other negative, masking now the space already printed. In printing the picture negative, light changes are made as usual; for the sound negative the light is regulated to result in 35 per cent transmission of the unmodulated track after positive development. Provision of suitable masks in the camera has been made to show in the finder and expose on the film only the portion which will be available for picture projection.

In the theater projector, the sound gate is located 14.5 inches below the picture gate, in order to project the sound record at a point where the film is in continuous motion. Therefore in the printing it is arranged to print the sound negative displaced along the length of the positive enough to bring the sound 14.5 inches ahead

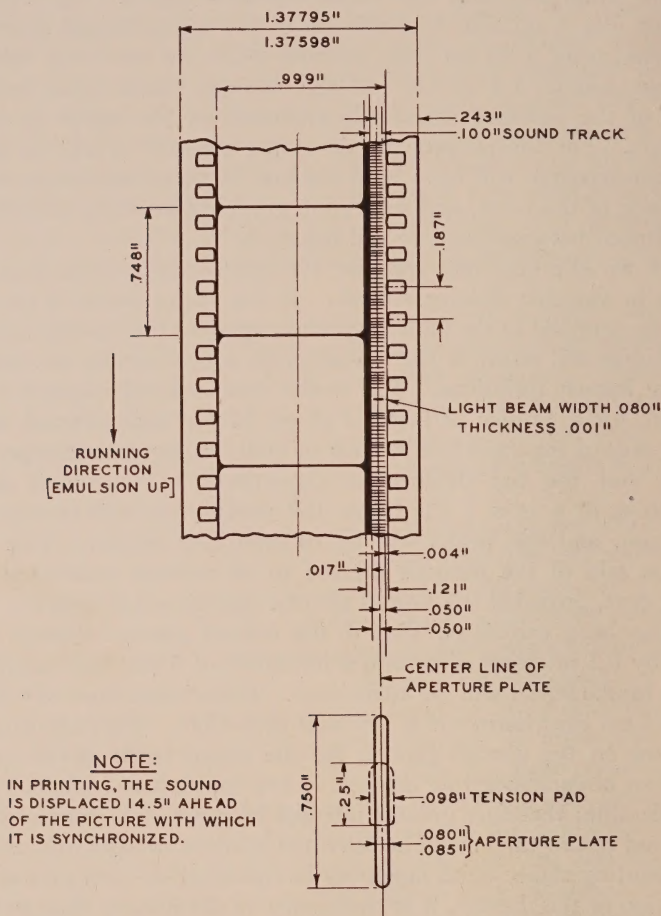


Fig. 5—Picture and sound track dimensions of synchronized sound film for standard 35 mm. positive stock.

of the corresponding frame. The printer apertures are chosen to give a dark no man's land 17 mils wide between picture and sound track; the latter at the outside is separated 4 mils from the inner perforation edge.

Fig. 5 exhibits the present practice for the finished positive. * It will be seen that the sound track covers 100 mils clear, and is illuminated

in the projector by a line of light 80 mils long, 1 mil wide, centered on the striations. This gives a margin of 10 mils at each end of the reproducing line, an allowance for lateral shifting of the film on the sprocket teeth.

In conclusion, let me estimate the quality of the sound record to be expected. Assume that the recording lamp current has been set to within 5 per cent of the theoretical optimum, the overall gamma held between 0.8 and 1.2, and the final average positive transmission is between 32 per cent and 38 per cent. Then the distortion of wave form due to photographic handling is so small that the ear can not distinguish the record from a theoretically perfect one. The frequency-amplitude characteristic of the reproduced sound remains to be stated.

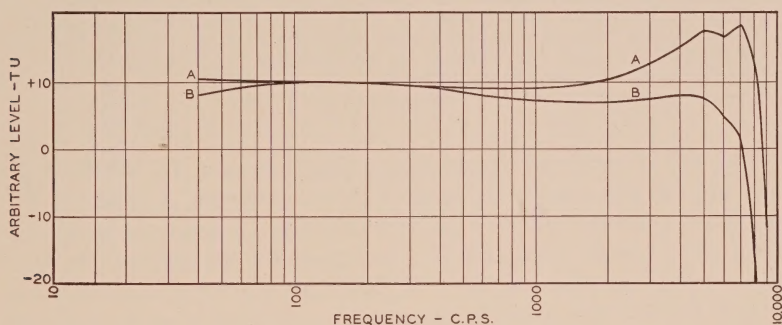
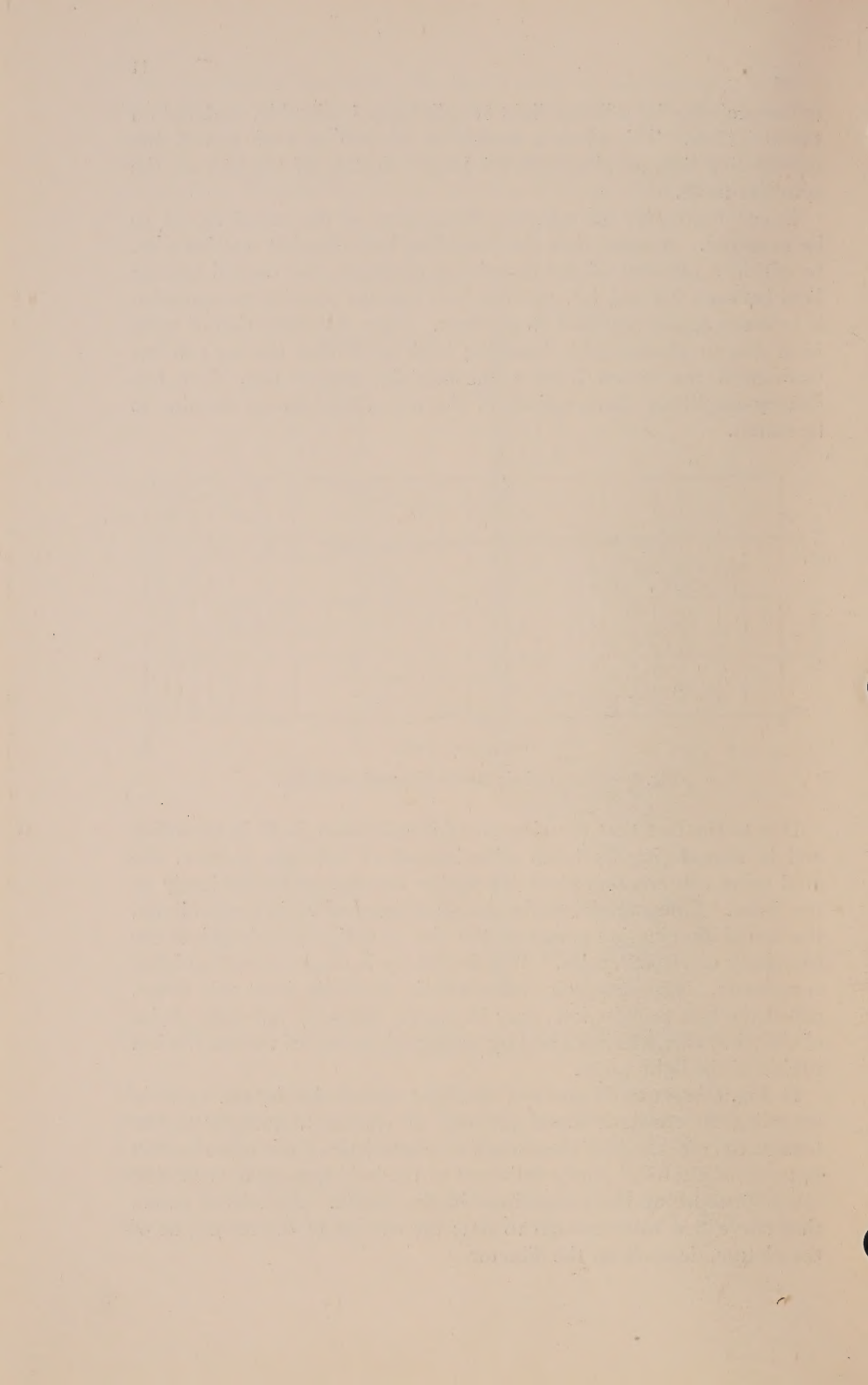


Fig. 6—Characteristic curves of sound recording.

Due to the fact that the element of illumination, both in recording and in reproducing, is 1 mil wide instead of infinitely narrow, the final print will not reproduce the higher frequencies as efficiently as the lower. For example, at the standard speed of 90 feet per minute, the line of illumination covers on the film an entire cycle length of the frequency of 18,000 cycles. This frequency is therefore extinguished completely. The drooping characteristic resulting from this effect, called the film transfer loss, may be largely offset by judicious choice of electrical characteristics and by taking advantage of the mechanical tuning of the light valve.

In Fig. 6 is shown in curve *A* the light modulation by the valve in recording for constant sound pressure of various frequencies at the transmitter; in curve *B* the overall characteristic of the reproduction in terms of electrical power delivered to the loud speaker for constant sound pressure at the transmitter in the studio. Experience shows that curve *B* is close enough to flat; the success of the record, as of the picture, depends on the director.



Synchronization and Speed Control of Synchronized Sound Pictures ¹

By H. M. STOLLER

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SYNOPSIS: The reproduction of the synchronized sound picture of today presents no serious problem of synchronization, for this factor has been practically eliminated by the perfection of electrical means for reproducing sound with equipment which may be coupled mechanically to the picture projector.

The important problem of the present day, in connection with the reproduction of synchronized sound pictures, is the provision of suitable means for maintaining a constant speed of the sound reproducing mechanism in order that the pitch of the sound being reproduced may not suffer any sudden change which would be sensed by a good musical ear. Control circuits using vacuum tubes with a frequency bridge as a speed standard with provision for manual variable speed control are described and explained for use with both A.C. and D.C. motors. Remote synchronization permitting the recording of pictures and sound simultaneously on equipment located some distance apart is obtained by a modification of the Michalke electric gear system.

WHEN Thomas A. Edison gave a demonstration of his talking motion pictures nearly sixteen years ago one of his chief problems was proper synchronization between his acoustic phonograph and the motion picture projector. It was then necessary to locate the phonograph behind the screen in order to make the sound appear to come from the picture. A system of belts and pulleys running from one end of the theater to the other was used to secure synchronization with the projector in the booth.

The development of the electrical reproducer has made it possible to locate the turntable and reproducing mechanism in the projection booth permitting a direct mechanical coupling between it and the projector. The horns are located behind the screen and electrically connected by wires with the electrical reproducer.

Thus there is no problem of synchronization in reproducing except to set the needle on the disc at the proper point before starting. However, such mechanical coupling between the projector and sound recorder (either of the disc or film type) makes it necessary to provide very close speed regulation on the projector motor, since variations in speed produce proportional changes in the pitch of the sound.

This paper will describe the speed regulating system employed in reproducing and the synchronization system used in recording.

¹ Presented before Society of Motion Picture Engineers at Lake Placid, New York, September 24, 1928.

SPEED REGULATION REQUIREMENTS

A good musical ear while having a sense of absolute pitch of only about 3 per cent is extremely sensitive to sudden changes in pitch. It has been found that a sudden change in pitch as small as one half of 1 per cent may be noticed if made abruptly. In order to properly take care of this requirement, therefore, the speed regulation or change in speed of the motor drive over normal variations in line voltage and load should be held within $2/10$ of 1 per cent.

The absolute speed must also be held near these limits since at the end of a film it is necessary to switch from one projector to another with minimum change in the pitch of the sound reproduction.

VOLTAGE, FREQUENCY AND LOAD VARIATIONS

A study of the voltage variations in power supply systems indicated a range from 100 to 125 volts. At a particular location the normal variation of voltage was found to be 5 per cent above or below the mean value with occasional momentary variations of as much as 10 per cent above and below mean value.

An investigation of variations in frequency of the supply voltage showed that in the large cities the frequency was held very accurately at 60 cycles. In New York City for example the frequency stays within one quarter of 1 cycle and does not change rapidly. However, in some small power systems the frequency varied as much as 5 cycles and in some cases was subject to rapid changes in frequency.

The load of the motor is due mainly to mechanical friction in the projector and take-up mechanism. This load was found to be on the average $1/10$ of a horse power but subject to wide variations. In the case of a new machine with a stiff adjustment of the take-up mechanism, the load was found to be as high as one-fifth of a horse power.

SPEED CONTROL CIRCUIT

A consideration of the variables just discussed imposes rather severe requirements of speed control, the two extremes being (1) the combination of low line voltage, low frequency and heavy load, (2) the combination of high line voltage, high frequency and light load. Ordinarily it might be possible to compromise and not provide for such an extremely unfavorable combination of requirements. However, it must be borne in mind that in the case of a musical program the failure of the speed regulating system for even as short a time as a fraction of a second would be a very serious matter causing the music to sound off pitch similar to a phonograph which has run down while in operation.

An examination of the standard commercial types of speed control indicated that there was nothing exactly suitable. The nearest approach to a suitable governor is the standard type of phonograph governor but this friction brake type of governor has serious objections if applied to a motor of considerable power output. In order, therefore, to have a control system which would be free from maintenance, it was necessary to develop a special form of control system for the purpose. Fig. 1 shows a photograph of the A.C. motor and its control cabinet.

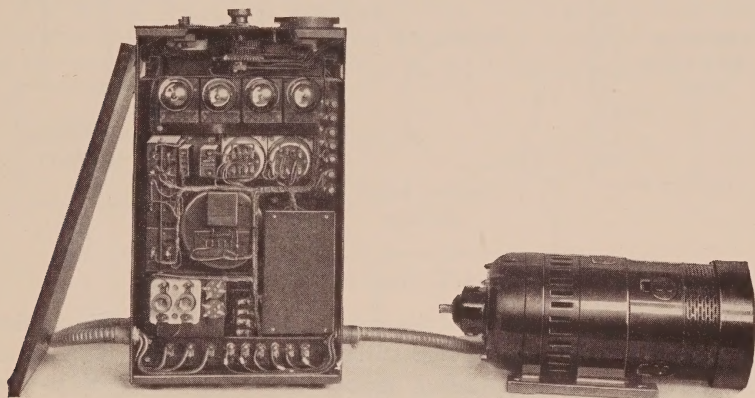


Fig. 1—A. C. Motor with control cabinet.

A.C. MOTOR CONTROL CIRCUIT

Fig. 2 shows the A.C. motor circuit which consists of a repulsion type of motor coupled to a small auxiliary alternator providing a frequency of 720 cycles which through a control circuit is made to operate a variable reactor across the armature terminals of the motor. If the speed of the motor is too high, the control circuit produces a maximum impedance in the reactor L_1 thereby reducing the armature current of the motor and causing it to slow down. While if the speed is too low the control circuit causes the reactor L_1 to have a minimum of impedance increasing the armature current and causing the motor to speed up.

This reactor L_1 is of the D.C. saturating type having two outer legs with A.C. windings and the middle leg with a D.C. winding. The A.C. flux circulates around the two outer legs. The D.C. flux flows from the middle leg and returns through the outer legs in parallel. When D.C. flux is sent through the middle leg it saturates

the outer legs thereby reducing their impedance to A.C. This type of reactance is old and was employed by Alexanderson as a magnetic modulator in his early radio work.

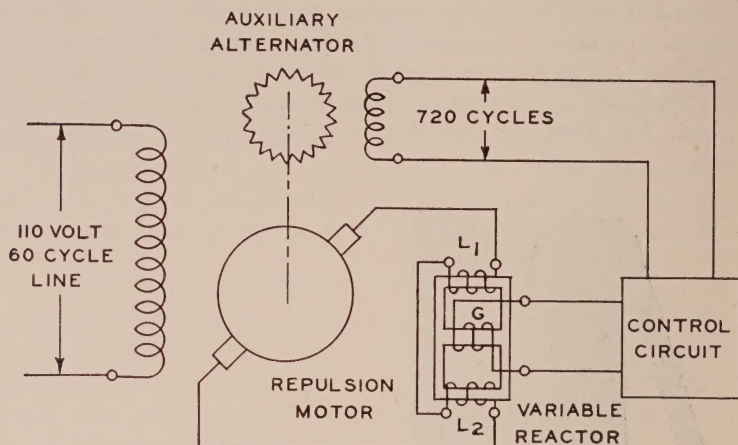


Fig. 2—A. C. Motor circuit diagram.

Fig. 3 shows one element of the speed control circuit. This consists of a bridge circuit having one variable arm and three fixed arms. The variable arm comprises a tuned circuit consisting of the in-

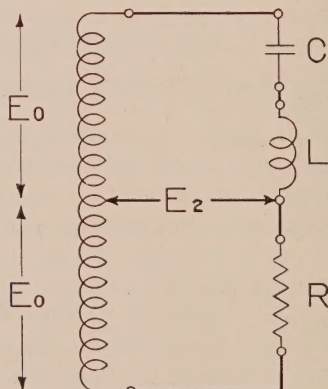


Fig. 3—Bridge circuit in speed control system.

ductance L and the capacity C which are designed to tune at exactly the frequency corresponding to the desired motor speed. When this circuit is in tune it has a resistive impedance which is balanced by the fixed arm R of the bridge. The other two fixed arms on the left

are windings of a transformer with a mid tap. If a voltage $2E_0$ having a frequency of 720 cycles (which is the frequency corresponding to the desired speed of 1,200 R.P.M.) is supplied to the bridge it will be apparent that the output voltage E_2 will be zero. If, however, the speed is low the tuned circuit will have a condensive reactance while if the speed is high it will have an inductive reactance. The output voltage E_2 will, therefore, change abruptly 180 electrical degrees from a speed below 1,200 to a speed above 1,200. This characteristic is shown in Fig. 4.

The use of the above described bridge circuit gives a very sharp characteristic due to the fact that the effective resistance component of the tuned circuit is balanced out by the adjacent resistance arm of

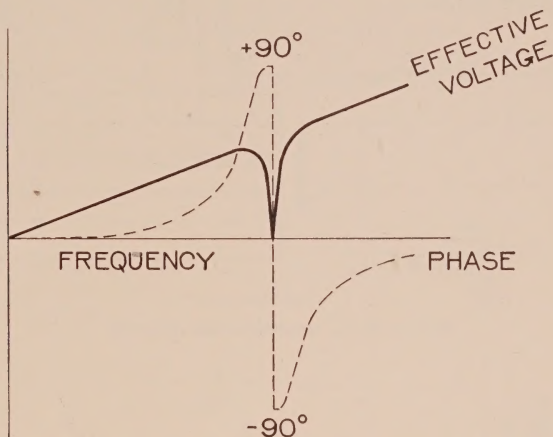


Fig. 4—Output voltage characteristic of bridge circuit.

the bridge. In this way an overall characteristic of the desired sharpness is secured using a comparatively small and inexpensive coil and condenser.

Fig. 5 shows the complete control circuit. The output from the bridge circuit is supplied to the grid of tube V_4 which is called the detector tube. The plate voltage of this tube comes from the 720-cycle generator through the step-up transformer T_4 . The phase of this voltage, therefore, remains constant. The phase angle of the grid voltage, however, comes from the bridge output circuit through the step-up transformer T_3 and as previously explained suffers a sudden reversal of phase as the speed passes through 1,200 R.P.M. Fig. 6 shows the resulting current coupling characteristic through tube V_4 . This current flows through coupling resistance R_1 which drives the grids

of tubes V_1 and V_2 negative. This in turn reduces the plate current through tubes V_1 and V_2 and hence through the D.C. winding of the inductance L_1 controlling the armature current of the motor.

Tube V_3 is a rectifier tube supplying excitation to the field of the

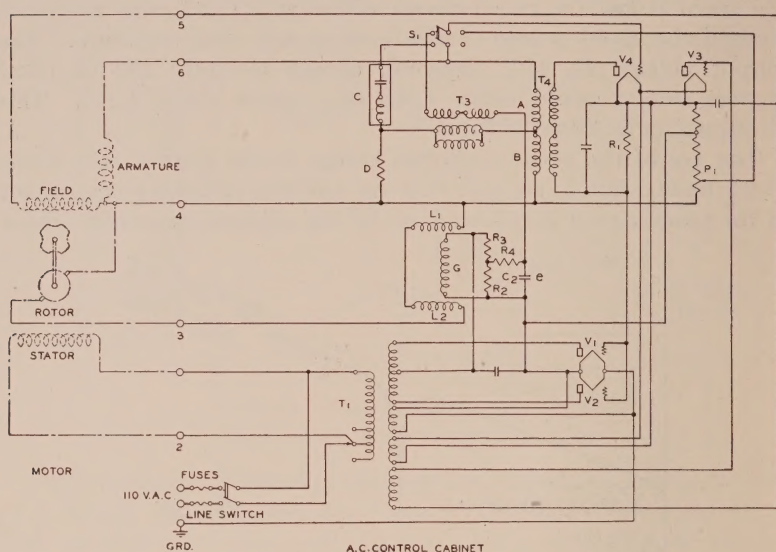


Fig. 5—A. C. control circuit diagram.

DETECTOR TUBE
SPACE CURRENT

FREQUENCY

Fig. 6—Characteristic of space current through detector tube V_4 .

720-cycle alternator and the negative "C" voltage along potentiometer P_1 .

Fig. 7 shows the performance characteristics of the motor. It will be noted that the actual speed characteristic is practically flat. This

flat characteristic is secured by a compensating network consisting of the resistances R_2 , R_3 and R_4 and the condenser C_2 . This compensating network feeds back on the grid of tube V_4 a portion of the voltage drop across the D.C. winding of inductance L_1 thereby correcting for the "static fluctuation" of the control circuit. By a suitable adjustment of this compensating resistance the control circuit may be arranged to give flat regulation, under regulation or even over regulation if desired. Fig. 7 has been drawn with line voltage as the variable. A similar characteristic is also obtained with load as the variable instead of voltage.

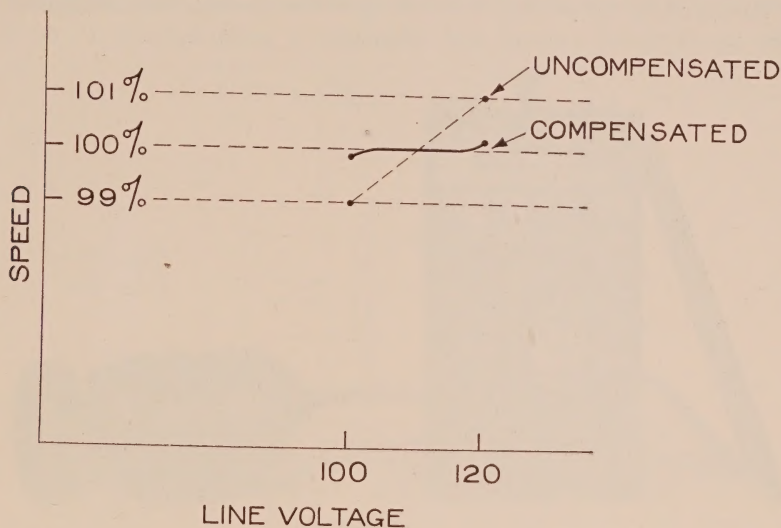


Fig. 7—Performance characteristics of motor.

An interesting point in connection with this compensation circuit is the necessity for avoiding hunting or surging of the speed. It is a well-known property of all forms of governors that if they are adjusted to too great a sensitivity the speed instead of remaining constant will fluctuate up and down about a mean value. The simplest method of preventing such speed fluctuations is to decrease the sensitivity of the governor allowing a bigger change in speed with load (or voltage) and then compensating for this change of speed or "static fluctuation" by means of a delayed action compensator. This phenomenon is well-known in the mechanical governor art and is described by Trinks in his book "Governors and the Governing of Prime Movers." The electrical equivalent of this mechanical system is obtained by intro-

ducing the condenser C_2 in series with the high resistance R_4 . When a change in current through the regulating reactance L_1 occurs the corresponding change in voltage drop is not transmitted to the condenser C_2 immediately, but C_2 changes its voltage after a certain time lag (approximately 1 second), required to charge the condenser through the resistance R_4 . The introduction of this time lag restores the precision of the circuit to the flat characteristic desired without introducing hunting.

VARIABLE SPEED OPERATION

By throwing the switch S_1 to the right the operator can disconnect the tuned circuit control and substitute a potentiometer P_1 as a

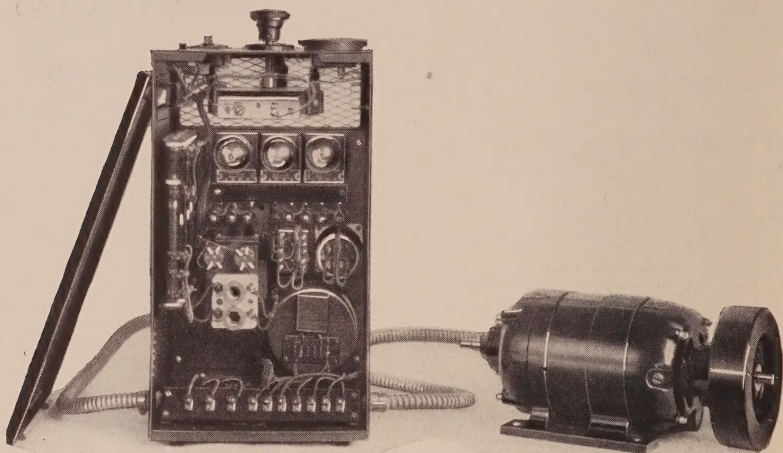


Fig. 8—D. C. motor with control cabinet.

source of grid voltage for tube V_4 . By means of this potentiometer the operator can adjust the speed of the motor at any speed from 900 to 1,500 R.P.M. corresponding to 68 to 112 feet of film per minute. This feature is employed for ordinary motion picture work where it is unnecessary to synchronize the picture with the sound. The regulation of the circuit under these conditions is sufficiently good for ordinary motion pictures.

An interesting feature in this connection is that theaters in many cases have preferred to use the regulated speed position for ordinary motion pictures as well as synchronized pictures. The reason for this being that with the speed of the projector precisely controlled the orchestra leader is better able to keep his orchestra in step with the picture indicating apparently that closer speed regulation than is

at present provided would be desirable for ordinary motion pictures as well as synchronized pictures.

D.C. CONTROL CIRCUIT

A circuit very similar to the one just described is employed in the case of the D.C. motor. Fig. 8 shows a photograph of this motor and its control cabinet. The circuit is shown in Fig. 9. It differs from the A.C. circuit in that an auxiliary regulating field winding is employed on the motor instead of a variable reactor. The source of power for the plates of the vacuum tubes is obtained from the auxiliary 720-cycle generator instead of from a 60-cycle transformer as in the

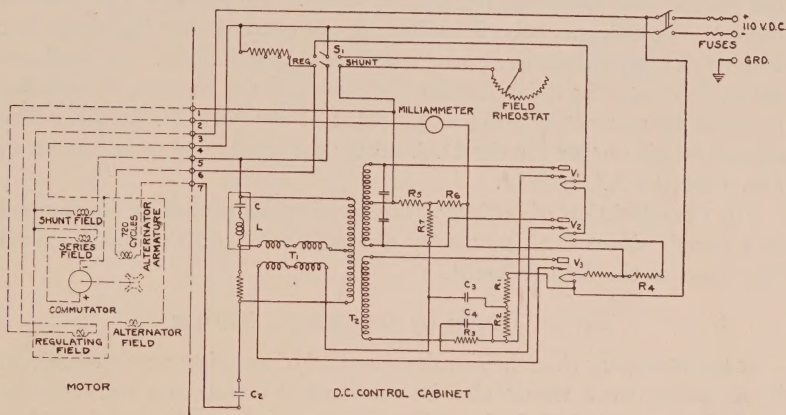


Fig. 9—D. C. control circuit diagram.

A.C. circuit. Since a strengthening of the field of the D.C. motor is required in order to reduce the speed it is necessary to reverse the phase relationship of the transformer T_1 , so that the current in the detector tube decreases at speeds above 1,200 instead of increasing as in the case of the A.C. circuit.

The operation of the circuit is as follows: When the line switch is first thrown the motor acts as an ordinary D.C. shunt motor and accelerates. At low speeds the output from the 720-cycle generator is low and consequently there is no plate voltage supplied to the tubes and no current through the auxiliary field winding. The field is, therefore, weak and the motor speeds up. This condition is maintained until the equilibrium speed of 1,200 R.P.M. is approached. The phase angle of the voltage supplied to the grid of the tube V_3 is then in phase with the voltage supplied to the plate so that the grid of the tube goes positive at the same time that the plate is positive.

This causes a current to flow through the coupling resistances R_1 and R_2 which drives the grids of tubes V_1 and V_2 negative, thereby keeping down the current through these tubes and hence maintaining a weak motor field. The motor, therefore, continues to accelerate until a speed of 1,200 R.P.M. is reached. At this point as previously explained under the description of the bridge circuit, the phase of the output suddenly reverses whereupon the grid of the detector tube goes negative at the same time that the plate goes positive, thereby cutting off the current through the detector tube V_3 and reducing the negative C voltage on the grids of tubes V_1 and V_2 . This increases the plate current through the regulating field thereby stiffening the field of the motor and checking its rise in speed. In practice the current through the detector tube is neither at one extreme nor the other but reaches an equilibrium at the speed of 1,200 R.P.M. A feedback network having the delay feature for prevention of hunting is included in the same manner as previously described for the A.C. circuit. The characteristic curves for the D.C. motor are similar to those shown in Fig. 7 for the A.C. motor.

For the operation of ordinary motion pictures the motor is changed to a simple shunt D.C. motor by the switch S_1 and the speed varied by means of the field rheostat.

MOTOR DRIVE OF RECORDING SYSTEM

It might appear that the simplest method of securing synchronization in recording work would also be mechanical connection between the recording machine and the camera. It has been found desirable, however, from a practical standpoint to have the camera movable with respect to the recording machine as the recorder has to be accurately lined up and adjusted and is not essentially a portable machine whereas the camera in ordinary motion picture work must be a portable piece of equipment. It has been necessary, therefore, to develop a motor drive equipment which will satisfactorily interlock the camera and the recording machine but leave the camera unit portable. It is essential that the interlock should hold not only during normal conditions but during acceleration and deceleration. In other words, the system must be the full equivalent of a mechanically geared system. The principle employed is old being disclosed in a patent issued to Michalke in 1901. In Fig. 10, A and B are two units which it is desired to interlock. Each unit has a three phase stator and a three phase rotor, the latter provided with slip rings. Magnetizing current for the system is supplied from an independent three phase, 60-cycle source. If the rotors of A and B are in exactly

the same positions with respect to the stators it is evident that the e.m.f.'s produced in them by transformer action will be identical as to voltage and phase. Consequently there will be no flow of current over the rotor leads and hence no torque developed. If, however, unit *A* is turned through a small angle then the phase of the e.m.f.'s produced in the rotor circuits will differ from that in *B* and a current will flow in the rotor circuits producing a torque which will tend to make unit *B* assume the same position as *A*. If *A* is rotated continuously *B* will follow it up to synchronous speed of the stator field at which point the torque will drop to zero since no e.m.f. is induced in the rotor of either machine.

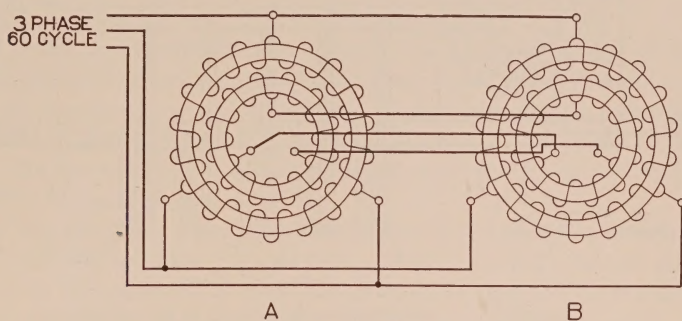


Fig. 10—Electrical driving gear.

COMPLETE RECORDING CIRCUIT

The portion of the circuit shown in Fig. 10, is merely the equivalent of a mechanical gear, neither unit tending to rotate as a motor by itself. In order to produce such rotation, therefore, a distributor set is added as shown in Fig. 11, the distributor acting, to use a mechanical analogy, as the driving gear of the system and each of the individual units of the system as driven gears. The distributor is itself driven by a D.C. motor provided with the speed control circuit previously described and shown in Fig. 9. The speed of the system is thus solely dependent on the D.C. driving motor and independent of the 60-cycle excitation frequency.

In practice the system is controlled by an operator at the distributor set and by means of switches any desired number of cameras, recording machines, or projectors may be employed. The projecting machines are used in case it is desired to make up a sound record to accompany an ordinary motion picture film which has previously been recorded without sound accompaniment. It has been found that the system operates very satisfactorily and requires very little maintenance.

When starting up for the first time it is necessary that the various units should line up properly as to phase otherwise there will be a local flow of current in the rotor circuits, which will cause the motors to operate as induction motors and run away. Under running conditions the system is very stable showing no tendency to hunt or surge between units, for the reason that being polyphase each phase as it becomes inactive (when the induced e.m.f. passes through zero) acts as a damping winding for the other two active phases.

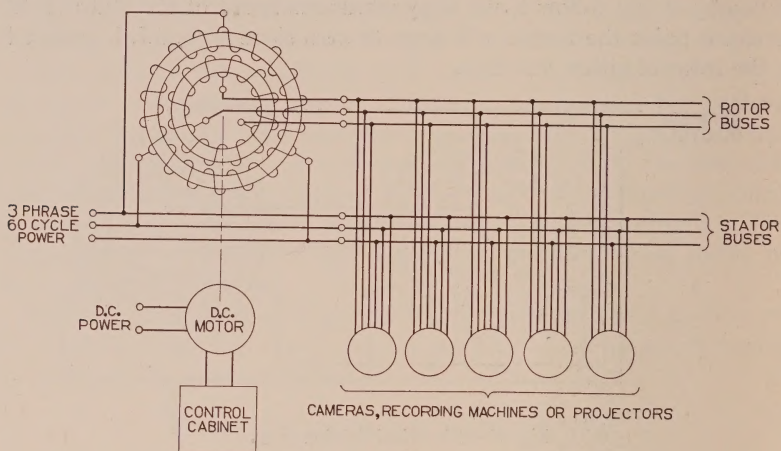


Fig. 11—Diagram of synchronizing system for recording.

If the load on a particular unit of this system is varied there will be a variation in the phase angle between this unit and other parts of the system in the same manner as in the case of a synchronous motor of the ordinary type. The magnitude of this phase angle, however, does not vary more than 30 electrical degrees or 15 mechanical degrees and is sufficiently small so that it produces an inappreciable effect on the synchronization.

DISCUSSION

The above described motor equipment with its associated control circuits has been in practical use for over a year both in recording and reproducing work and there have been practically no troubles in service.

In the design of this equipment, first consideration has been given to its precision and reliability in operation and the provision of adequate margins to care for all variations in service conditions. As a result it has been possible to maintain a high standard of quality in music and speech reproduction.

A Sound Projector System for Use in Motion Picture Theaters¹

By E. O. SCRIVEN

Bell Telephone Laboratories

SYNOPSIS: The general problem involved in the design of a system suitable to be used to record and reproduce sounds such as are required for "talking" motion pictures is outlined. The general method of attack is indicated. There follows a description of the several pieces of apparatus which comprise the theatre equipment, including a discussion of some of their salient features and of the part each plays in the sound projector system.

IN order to reproduce in a theater the pictorial record of events accompanied by the sound associated with those events, it is, of course, necessary to add equipment to that installed to produce only the silent motion picture. It is the purpose of this paper to outline and discuss briefly the major items of such equipment as developed by Bell System engineers.

In the design of sound equipment a primary requisite is that there shall be freedom from distortion. Distortion may be of the sort which is independent of load and is evident in that the intensity of some portion or portions of the sound spectrum is increased or decreased in comparison with the rest; or there may be the distortion which is a function of the level at which the device is operated and is characterized by the reduction of a pure tone into fundamental and one or more harmonics. This latter condition is most often the consequence of operating a vacuum tube amplifier above its proper energy handling capacity.

It is the resonances of vibrating strings or reeds or air columns or vocal cords that give us the music we record but we are careful that a minimum of the resonances of the recording system itself shall go into the record, and that any resonances of the reproducing system shall not appear in the output of the sound projectors. Aside from the effects of overloading, the prevention of distortion is largely a matter of getting away from resonance phenomena since it is the characteristic of the resonant system to respond with disproportionate amplitude to stimuli in the region of its own natural period. The whole story of the passage from sound energy through the various recording and reproducing devices back to sound energy again is one of contest with this fundamental physical phenomenon.

¹ Presented before Society of Motion Picture Engineers at Lake Placid, New York, September, 1928.

There are in general two things one can do to avoid the harmful effects of resonance in vibration transmitting or transforming apparatus: (1) the period of resonance of each piece of equipment can be moved outside the range of frequencies one wishes to transmit, at the same time providing damping means to minimize free vibrations; (2) the distortion produced by resonance in one piece of apparatus can be compensated for or equalized by similar and opposite distortion

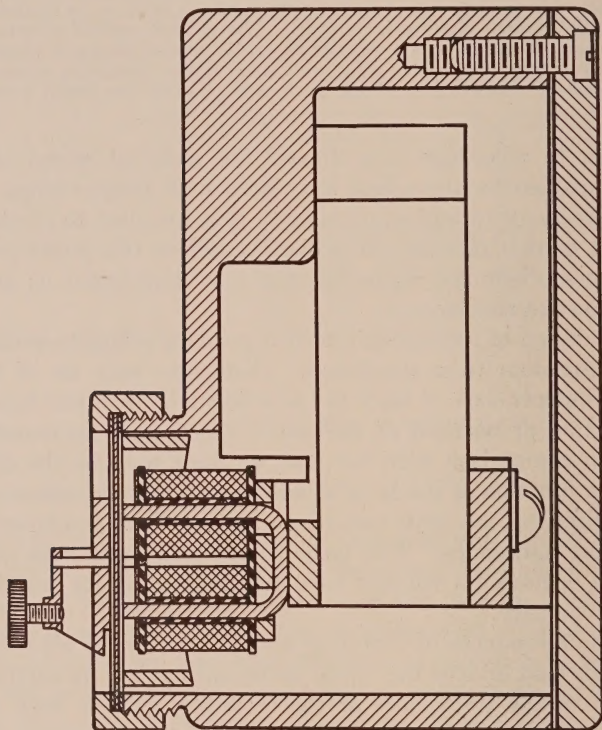


Fig. 1—Reproducer for disc record.

in some associated apparatus. The first is not always easy of practical accomplishment in any particular device and generally results in an instrument of very low inherent efficiency; the second usually involves loss of energy. In both cases increased amplification is required.

The sound record comes to the theater either as a wavy groove in a composition disc or as a striated track of varying density at one side of the picture film. It is the function of the apparatus being considered to derive from these records an electric current in which

all the variations in pitch and loudness are accurately represented, to suitably amplify this current, to effect its conversion into sounds approximating those from which the records were made, and to so direct those sounds as to reasonably create the illusion that sound and picture are cognate.

The disc records do not differ essentially from those used in the ordinary phonograph except that they are considerably larger and run at a much slower speed so that a single record will play throughout an entire reel. The reproducer used is in some ways similar to that

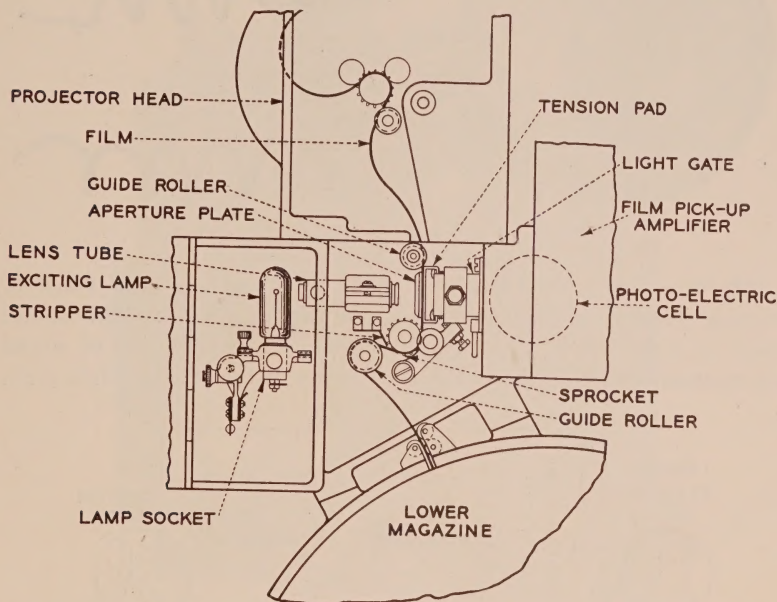


Fig. 2—Diagram of motion picture projector equipped for reproducing sound from film.

used on the acoustic phonograph, the needle holder being connected to a clamped diaphragm. This diaphragm is of highly tempered spring steel and to it there is fastened an armature made of a special high permeability alloy and so arranged that as the diaphragm vibrates the flux in the air-gap of a permanent magnet varies correspondingly, thereby inducing in appropriately placed coils currents which are the electric representation of the wavy groove which the needle travels. This reproducer is shown in Fig. 1. Although the energy delivered by this instrument is comparatively low it has a very uniform response over a wide frequency range. This result is largely brought about

by moving all resonances out of the working range and by filling the magnet chamber back of the diaphragm with a heavy damping oil. The film used with the disc record, called a synchronized film, differs from ordinary film only in that one frame at the beginning is specially marked to give the starting point.

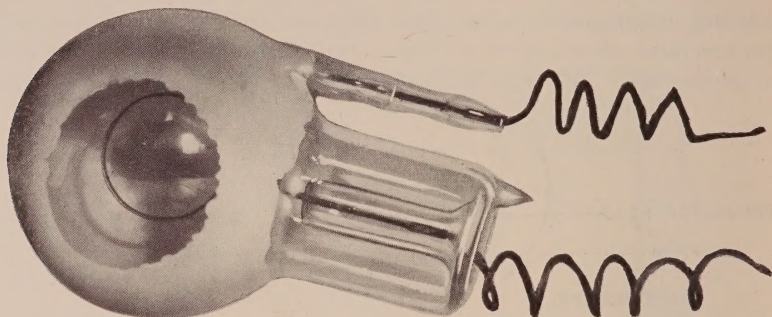


Fig. 3—Photoelectric cell.

The film sound record, as has been said, consists of a track of varying density running along one side of the picture. This sound track is $1/10''$ wide. Differences or changes in intensity of sound are represented by differences in the density of the record, while pitch

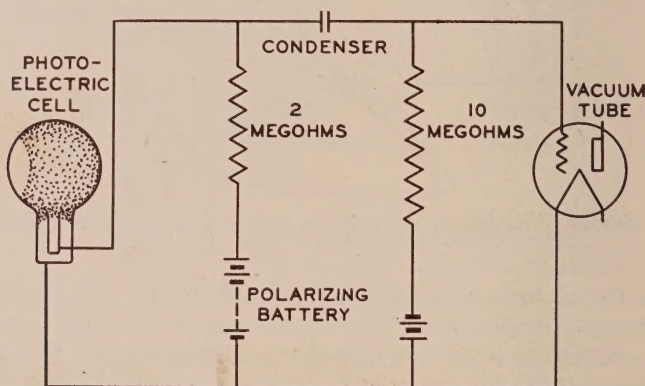


Fig. 4—Photoelectric cell circuit.

is represented by the number of changes from dark to light and back again in a given length of track. This sound record is converted into a corresponding electric current by arranging that a narrow high intensity beam of light shall pass through it and fall upon a photoelectric cell. The arrangement is shown in Fig. 2. The light from

the bright filament of the exciting lamp is focused as a very narrow line upon the film by passing through a system of lenses and an aperture plate. The lamp filament is focused upon a slit of dimensions $.0015'' \times 3/16''$. The image of this slit is then brought to focus upon the film as a $.001''$ line whose length has been reduced in passing through the aperture plate to $.080''$. This reduction in length allows $.010''$ on either side for variations in position of the $.100''$ sound track. The position and focus of the lens tube are fixed, but the carriage of

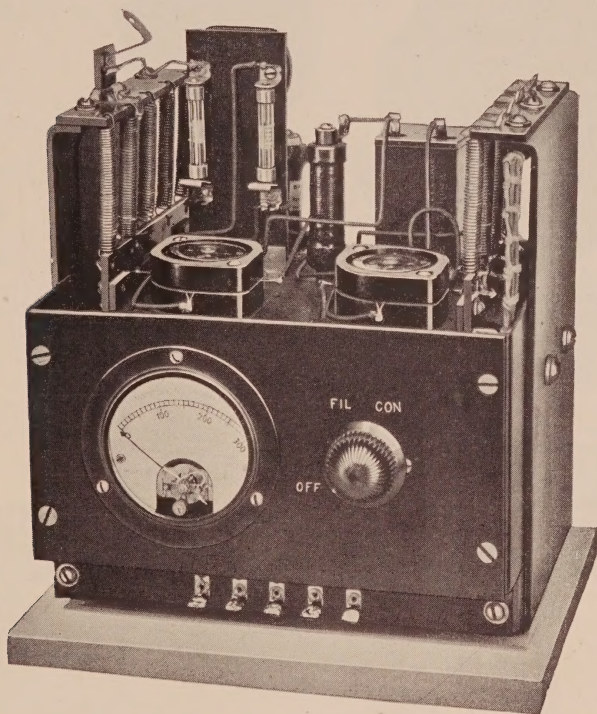


Fig. 5—Amplifier used at projector.

the exciting lamp is movable so that when replacing lamps the filament may be properly brought on focus.

A photoelectric cell of the type used is shown in Fig. 3. The characteristic of this device is that when it is polarized by a proper voltage and is used within proper limits the current through it is proportional to the incident light. The circuit is shown in Fig. 4. It is to be noted that the polarizing voltage is supplied to the photo cell through a very high resistance and there is, therefore, obtained across

this resistance a voltage which is proportional to the light falling upon the cell and accordingly bears a direct relation to the varying density of the sound track interposed between the exciting lamp and the cell.

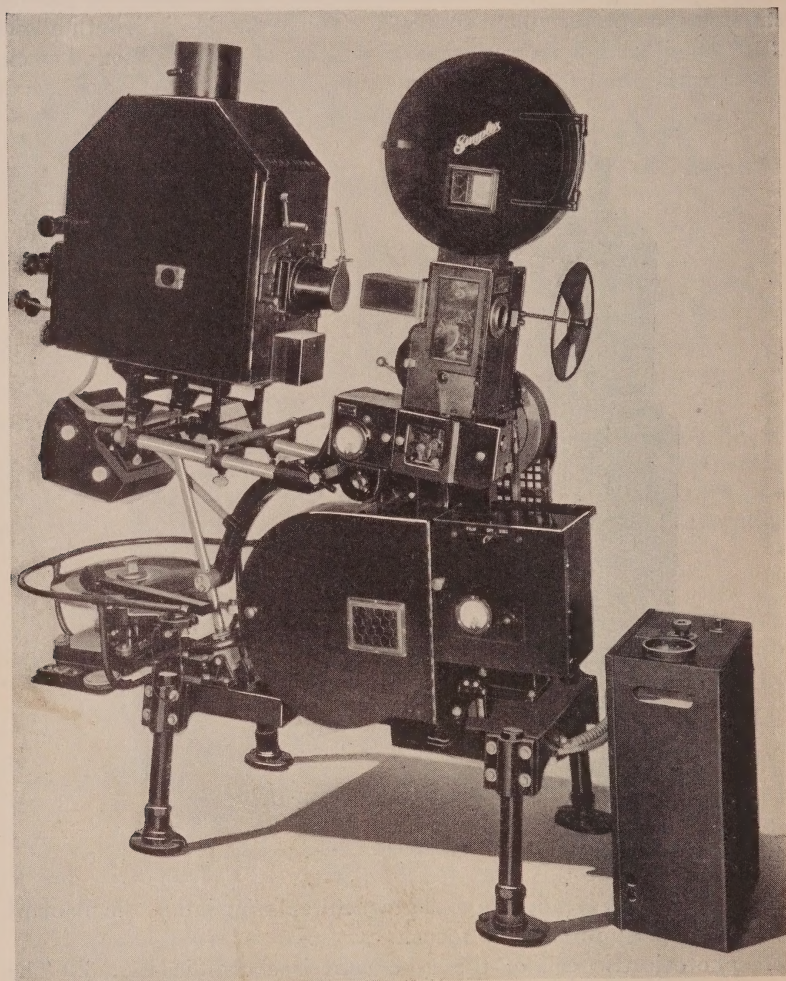


Fig. 6—Sound projector equipped with Simplex head.

The photo cell circuit is inherently one of high impedance. In such a circuit there are two matters which require attention. (1) Local interference—"static," to use the radio expression, is most readily picked up, and at this point where the energy level is low,

may be appreciable in comparison with the sound currents themselves; (2) also the shunting effect of capacity between the electrical conductors becomes noticeable, particularly at the higher frequencies.

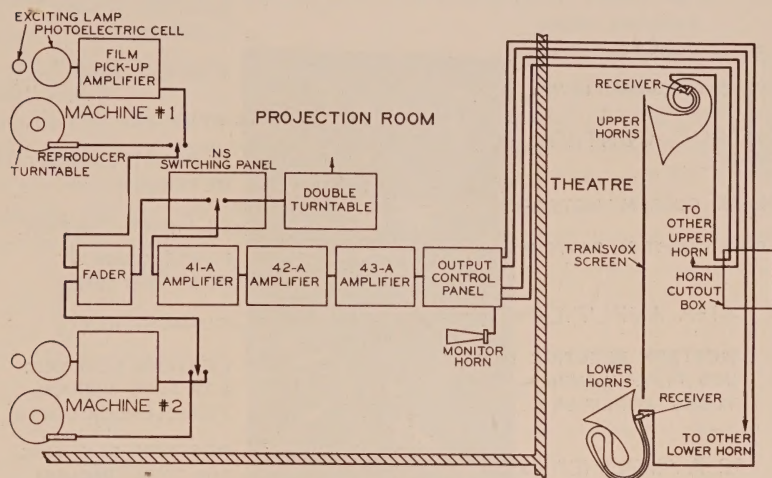


Fig. 7—General layout of equipment.

Hence a vacuum tube amplifier, which serves both to increase the energy and to make that energy available across a low impedance circuit, is closely associated with the cell upon the projector itself.

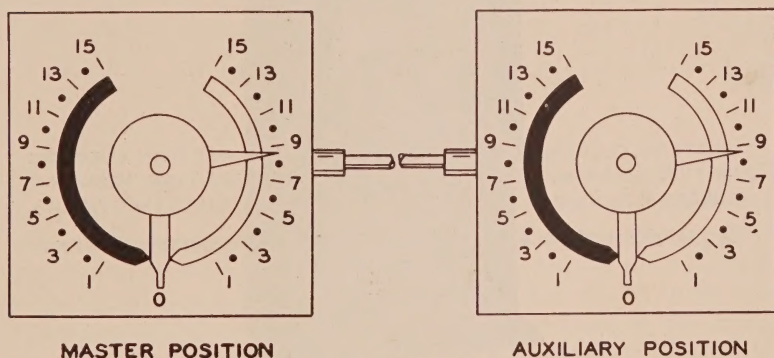


Fig. 8.

The cell and amplifier are enclosed in a heavy metal box or shield which is made fast to the frame of the projector and the projector itself is carefully grounded. This amplifier is shown in Fig. 5. It is designed to bring the level of the electric counterpart of the film sound

record up substantially to the same energy value as that obtained from the magnet coils of the disc reproducer. The filaments are heated from a 12-volt storage battery. Small dry batteries supply its plate

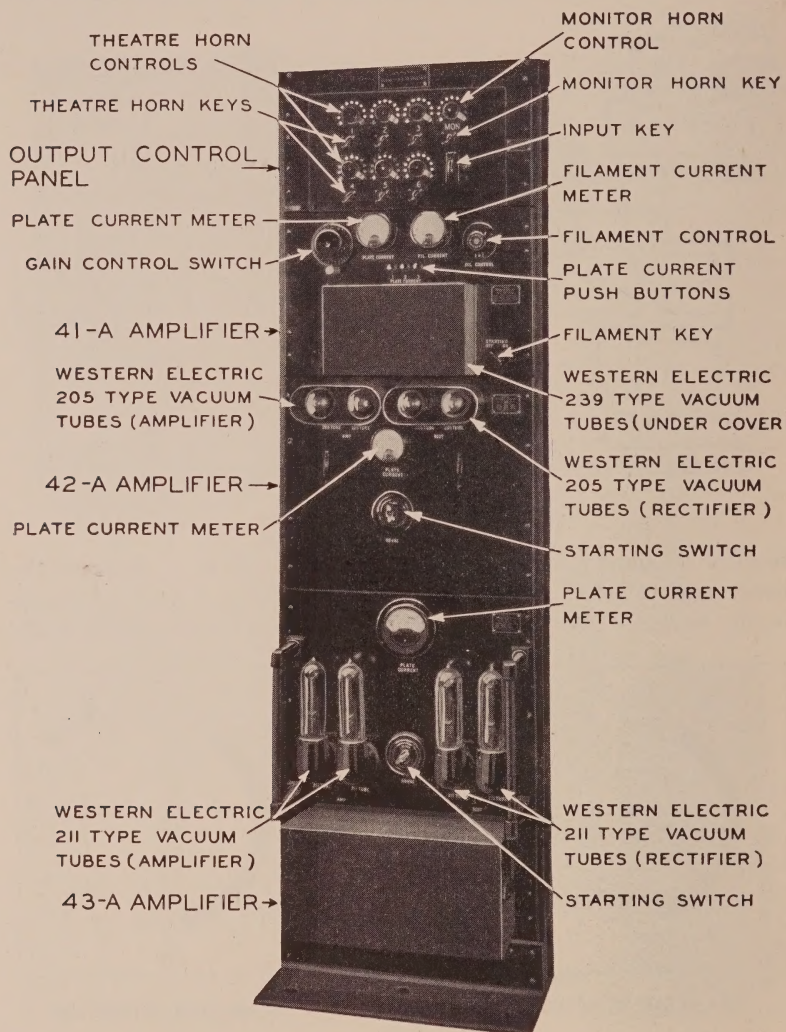


Fig. 9—Amplifier Panel.

current and also the polarizing potential for the photo cell. These batteries and the battery leads are shielded.

Vibration of a vacuum tube often produces sufficient motion of its elements with respect to each other to effect changes in the stream

of electrons which appear when sufficiently amplified as noise from a loud speaker. In spite of all precautions there is a certain amount of vibration of the projector when in operation and it has therefore been necessary to design a rather elaborate shock-proof mounting for the photo cell amplifier.

It is evident from the relative location of apparatus as shown in Fig. 2 that it is not feasible to print the film sound record directly beside the picture to which it applies. As a matter of fact, there is a spacing of $14\frac{1}{2}''$ between picture and corresponding sound record and a certain amount of slack is allowed between the sprocket which carries the picture with an intermittent motion before the picture projection lens and the sprocket which must carry the sound record

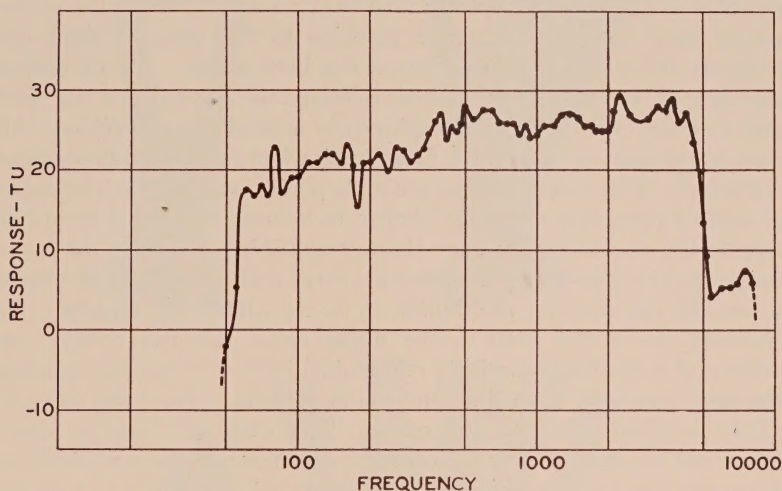


Fig. 10.

with a uniform motion in front of the photoelectric cell. In this connection it is noteworthy that special precautions are necessary in order to prevent vibrations and speed fluctuations due to either varying supply voltage or varying load from affecting the uniformity of rotation of this sound sprocket. This is taken care of by the very effective means of automatically controlling the speed of the driving motor and by means of a mechanical device interposed between the sound sprocket and the rest of the moving equipment of the projector which effectively opposes the transmission of any abrupt change of speed to this sprocket.

The control box which contains the apparatus for governing the speed of the driving motor is arranged to hold the record speed the

same as that at which the records are made, i.e. 90 feet per minute in the case of synchronized sound and picture productions. By throwing a switch the automatic feature may be cut out and the speed of the machine may then be manually controlled by the operator.

This completes the apparatus associated directly with the projector. The general arrangement of the latest type of projection machine, equipped with a Simplex head, is shown on Fig. 6. Incidentally this projector is also arranged to be fitted with the Powers or the Motiograph head. Fig. 7 shows a typical layout of a sound projector system as installed for use with talking motion pictures.

As in ordinary pictures, in order to run a continuous program, it is necessary to use two projectors alternately. As the picture from one machine is faded imperceptibly into that on the other so the sound record may be faded from one machine to the other without the audience being aware that a change has been made. At the end of each record or sound film the music overlaps the beginning of the next and a device called a fader is employed in making the transition. All that is necessary is to turn the fader knob when the incoming machine is started. This fader is in fact a double potentiometer. In the upper or normal operating range the change in volume in moving from one step to the next is hardly more than perceptible whereas in the lower range used only in fading the steps are large and the volume decreases to zero on one machine and builds up on the other very rapidly. By choosing the proper step in the upper range one can obtain any volume of sound desired within reasonable limits and thereby equalize the level obtained from different sound records. The fader is ordinarily installed with one or more auxiliary dials and handles interconnected so that it may be operated from any projector position. In connection with the fader there is provided a switch for changing from the film to the disc input system and also a key for switching a spare projector in place of either of the regular machines. Fig. 8 shows a fader with one auxiliary position.

Following the fader, we come to the main amplifier which raises the energy of the feeble electric currents to a level adequate to supply the loud speakers with sufficient volume to serve the particular theater. Fig. 9 shows a typical amplifier panel. This combination is capable of an energy amplification of about 100,000,000 times and is so designed that all frequencies in the range from 40 to 10,000 cycles are amplified practically equally. A potentiometer is provided on the amplifier but while its handle is readily accessible it is ordinarily not used after having once been set at the time of installation to give proper results in the particular theater. Necessary adjustments are

made on the fader. The amplifier shown consists of three units. The first consists of three low power tubes in tandem, resistance coupled, and requiring a 12-volt battery delivering $1/4$ ampere to heat their filaments. The second consists of a single stage of two medium power tubes, connected in push-pull arrangement with filaments

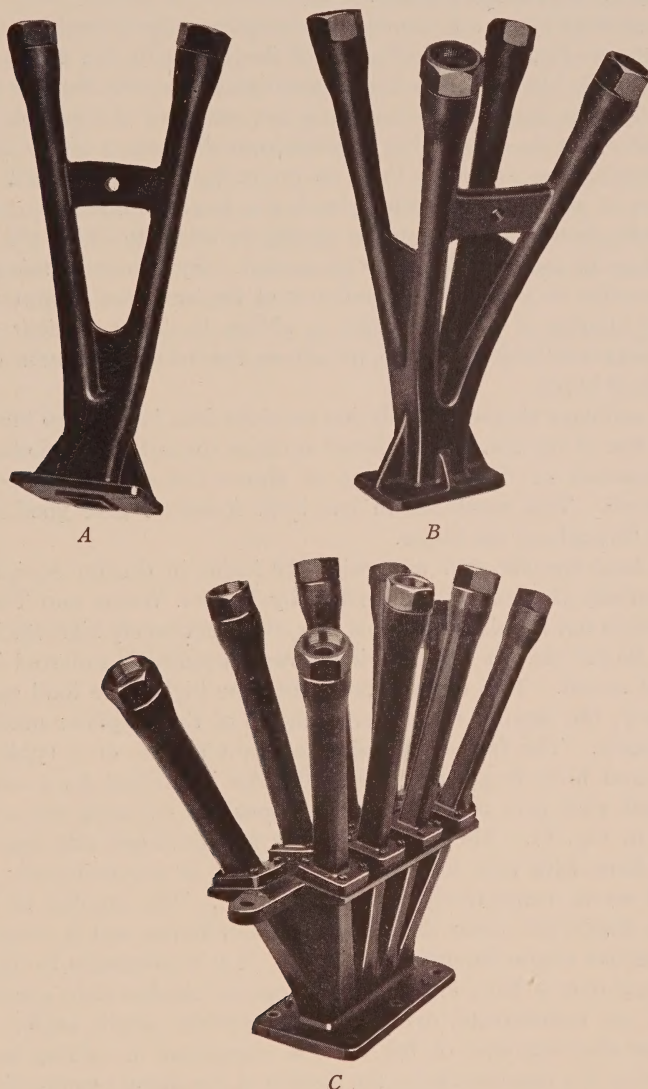


Fig. 11.

heated by low voltage alternating current. Two similar tubes in this unit operate as a full wave rectifier and supply rectified alternating current for the plate circuits of the amplifier tubes of both the first and second units. The third unit has a single stage of high power push-pull amplifier tubes and push-pull rectifier tubes and also operates entirely on alternating current.

These three types are capable of arrangement into combinations to meet the particular need. For small theaters only No. 1 and No. 2 are required. In the larger houses the high power unit No. 3 is added, while to meet exceptional conditions two or more of the high power amplifiers may be operated in parallel from the output of No. 2.

Following the amplifier there is an output control panel. This consists of an auto-transformer having a large number of taps, the taps being multiplied to a number of dial switches, to which the sound projectors or loud speakers are connected. By means of this panel, it is possible to match the impedance of the amplifier output to the desired number of horns in order to obtain the most efficient use of the power available and also to adjust the relative volume of the individual horns.

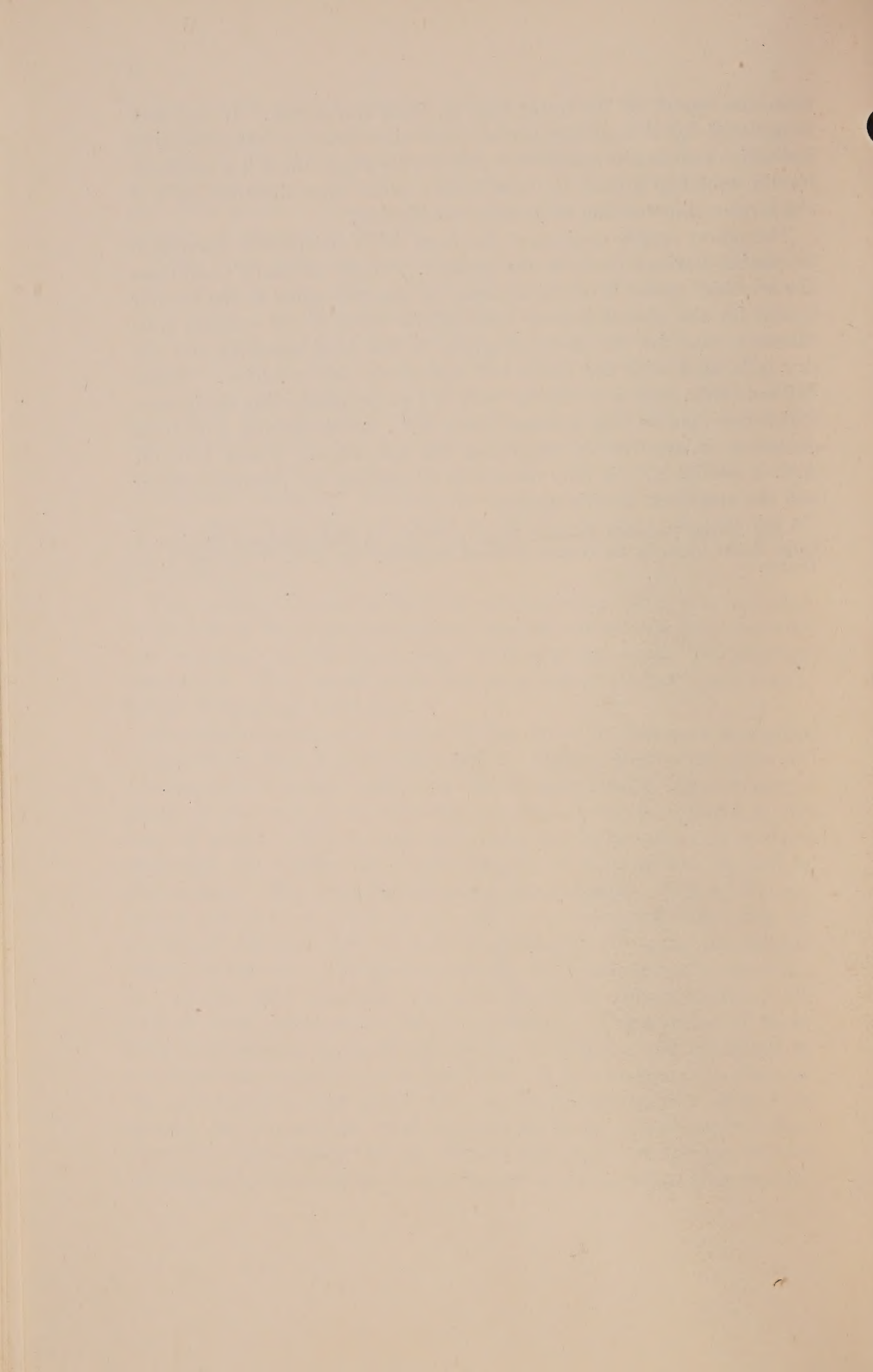
The ordinary theater installation employs four horns, two mounted at the line of the stage and pointed upward toward the balconies and two mounted at the upper edge or above the screen and pointed downward. This combination has been found to give good distribution throughout the house.

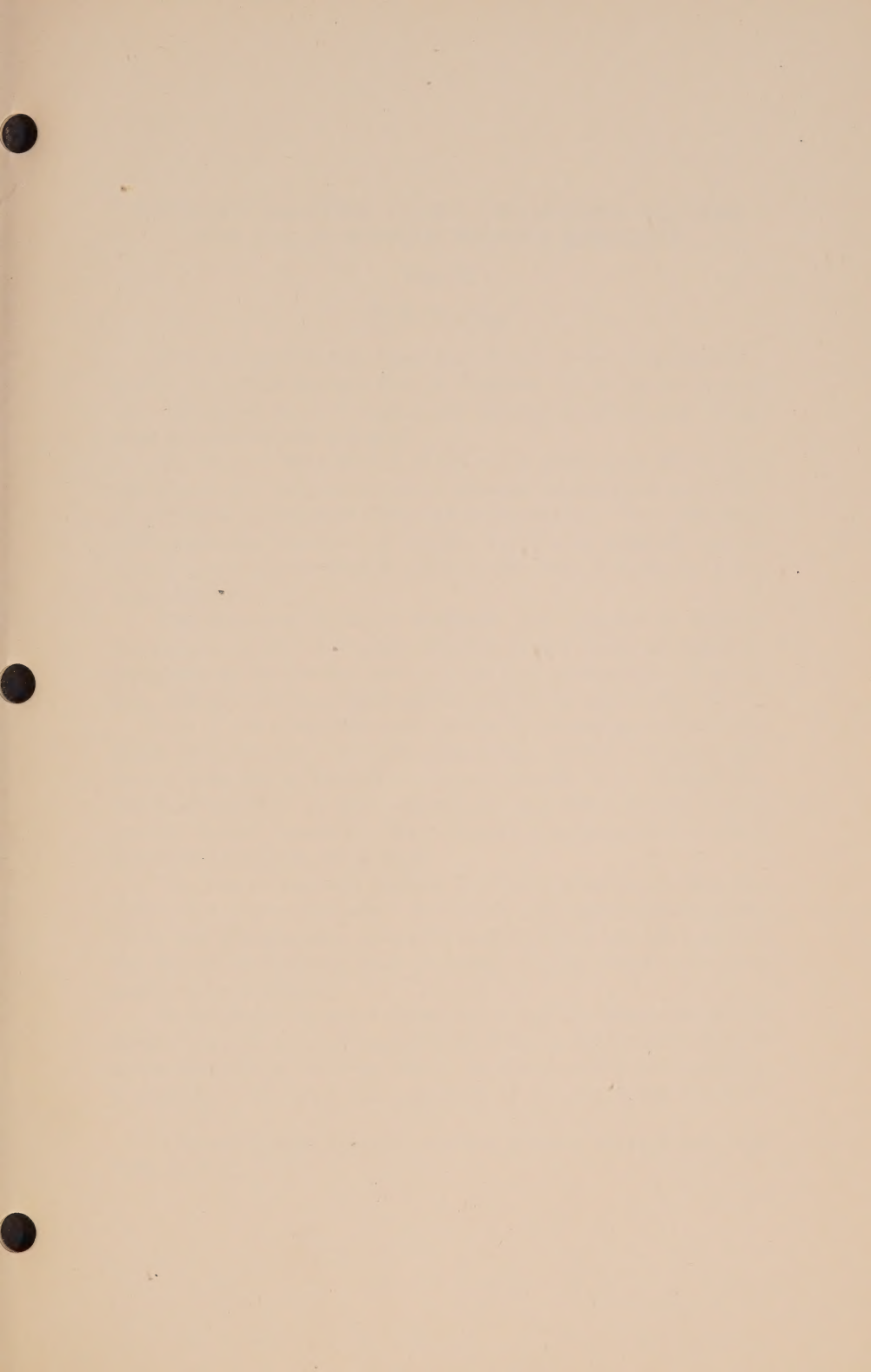
The loud speaker unit used with the horns in theater equipments is essentially that recently described by Messrs. Wentz and Thuras.² As brought out in this article, this unit shows extremely high efficiency; about 30 per cent of the electrical power supplied is radiated in the form of sound. This is important since the higher the loud speaker efficiency, the smaller the power capacity of the amplifier needed in the system. The frequency-response characteristic of a typical receiver and horn is given in Fig. 10. An individual horn may be equipped with two, four or nine loud speakers by using the throats shown in Fig. 11. The power capacity for continued safe operation of the horn with one, four and nine throats is approximately 5, 20 and 45 watts, respectively (electrical input). The number of horns used is dependent upon the particular installation and is related to the directive characteristic of the horn. If it is necessary to disperse the sound over a large angle, more horns are needed than when it is desired to concentrate over a comparatively small angle. This directive characteristic of the horn is important in talking motion pictures as it is responsible for the illusion of the sound coming directly

from the mouth of the horn; that is, from the screen. If the horn is replaced by a loud speaker of otherwise identical characteristics but which radiates its sound over a very wide angle, there is a tendency for the sound to appear to come from a point some distance back of the screen, thus tending to destroy the illusion.

The power supply equipment has been fairly completely covered in discussing various parts of the system. Under ordinary conditions the requisite power is obtained from the electric mains in the theater except for the 12-volt battery required for some of the vacuum tube filaments and for the electromagnets in the loud speakers and the dry cells used with the photo cell and photo cell amplifier. Where 110-volt D.C. only is available there is a projector-driving equipment which operates on this voltage, but a D.C. motor driving a 60-cycle generator is required for supplying the amplifiers. Where 110-volt A.C. is available, it is only necessary to connect the projector motor and the amplifiers to this supply.

² *Bell System Technical Journal*, January, 1928—"A High Efficiency Receiver of Large Power Capacity for Horn-type Loud Speakers," by E. C. Wentz and A. L. Thuras.





WESTERN ELECTRIC SOUND PROJECTING SYSTEMS FOR USE IN MOTION PICTURE THEATRES

Part II

H. B. SANTEE*

The first part of this paper has described the equipment employed for sound reproduction in theatres. It is the purpose of this, the second part, to explain the manner in which such equipment is installed and operated.

To obtain a clear picture of the whole problem in all its complexities, it will perhaps be best to consider an installation from its very inception and follow it through to completion. This treatment, while including mention of details which may possibly appear superfluous, will nevertheless present a fair idea of the scope of the work involved.

The Electrical Research Products, Inc. supplies to theatres the equipment of the Western Electric Sound Projector Systems, supervises its installation, instructs the local personnel in its operation, and provides inspection service during its subsequent use.

One of the most important factors in preparing a theatre for sound projection is the initial engineering survey, for upon this survey rests the decision of the type of system to be installed and the determination of requirements for apparatus layout and of possible special treatment. Each theatre is an individual problem and must be considered as such.

The survey engineer gathers pertinent information and prepares his recommendations. And while his recommendations are given due consideration, a special staff at the home office studies the survey and renders final decision. Survey information must therefore be complete.

In the projection room the engineer must investigate the power supply not only as to voltage and kind but to determine if there is ample capacity to carry the load to be added, and if the regulation is suitable. The type and condition of the projection machines

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must be noted and the angle of projection learned. Is the space between machines ample for the attachment of the sound apparatus and for convenient operation? Is there an acceptable location in the room for the amplifying equipment and associated controls? It is sometimes necessary, particularly in the older theatres, to require rearrangement of the projection equipment or possibly an enlargement of the projection room. Such changes are naturally welcomed by the operating staff. Space, conveniently near but separately enclosed, must also be found to house the storage batteries.

The auditorium presents an item for careful study, for upon its characteristics is based the size of the system to be installed. The types of systems available, varying in power output, meet conditions imposed by theatres from the largest to the smallest and are so arranged and selected that, while sufficient sound volume is at hand in each case, no theatre is overburdened with excess.

As blue prints of the auditorium are not always available it is frequently necessary for the engineer to take the dimensions himself, for the cubical volume is an important factor. Seating capacity and the distribution of seats also bear influence. The general acoustics of the house must be considered. What degree of reverberation is present, bearing in mind the absorptive effect of the audience. Are there areas of echo or interference or of otherwise bad hearing? Are internal or external disturbing noises a factor? A final and specific study of acoustic properties can best be made at the time of system testing upon completion of the installation, but general effects can be and are observed during the survey process.

The stage must receive consideration as to size and to layout with reference to location of the horns and of the special screen used with the system. If the theatre policy covers the showing of moving pictures only, the horns may be located permanently on a suitable structure. If vaudeville or stage presentations are included, however, they are generally placed in movable horn towers or else flown from battens.

Information sufficient to permit a knowledge of the conduit runs for the complete installation is also obtained at the time of survey.

The data collected, augmented by sketches prepared by the engineer, in conjunction with blueprints of the building, if available, thus provide the home office survey staff with a complete

picture of the theatre. The type of sound projector system is accordingly selected and the dates of shipment of equipment and installations are placed on schedule. If, perchance, architectural changes in the theatre are required the theatre management is so notified in the anticipation that alterations will be completed prior to the actual introduction of apparatus.

At the outset of an installation, it is important for the engineer to establish satisfactory personal contacts with the local people and organizations that will be related to the work. This is necessary that the work may proceed smoothly and without delay, as an opening date has by this time usually been fixed. While sufficient time for the installation, testing and rehearsals is allowed, obviously no large safety factor can be tolerated. The engineer first meets the house manager, and subsequently the projectionists, the house electrician and stage hands, and familiarizes himself with house conditions such as policy, house hours, labor conditions, best time for work, etc. It is necessary for him to find a competent electrical contractor, one, if possible, who already has knowledge of the theatre.

The installation proceeds in accordance with a logical plan. It is usual first to attach the driving equipment to the motion picture projector, for, while the projector mechanism itself remains practically intact, its driving motor is replaced by one with electrically regulated speed control. A film speed of 90 feet per minute is assured for sound picture work, but variable speeds may be obtained, if desired, for silent film. As these motors require four or five seconds to pick up speed, it is advantageous to have the projectionists become accustomed to such features in order to be able to give full attention to the handling of film or disc record when the time arrives.

The battery equipment is next installed with its switching panel and charging apparatus. This permits an investigation of the condition of the batteries and ample time for charging if required. Furthermore, the projectionists may study this portion of the apparatus at some leisure and have explained to them proper schedules of charging. If a motor generator is required, it is set up at this time.

The amplifiers and associated equipment are placed upon the relay racks and the fader with its auxiliary positions is mounted at the front of the projection room wall. The position of the monitor

horn is carefully selected so that the operating personnel will at all times be able to hear clearly, for it is by following the program through this horn that fader change-overs are made.

While the apparatus is being placed in position the conduit installation keeps apace. It should now be possible to connect the storage batteries and A.C. supply to the amplifying equipment and check its functioning. The fader can be electrically joined to the film and disc reproducers associated with the production machines. A film-disc transfer panel is mounted above the master fader position to permit either the film or disc reproducers to be used at will, simply by momentarily depressing the proper push button. A signal light gives visible evidence as to which circuit is set up. Interconnections between physically disassociated groups of equipment are made through a junction box located in the projection room. This method not only facilitates installation but provides a ready means for circuit checking and trouble finding.

While equipment and installation methods are constantly being simplified, it may be noted that a rather marked advance in this direction is to be introduced within a few months. At the present time the driving motor and disc turntable have their separate mounting pedestals. The film reproducer and associated amplifier are supplied as separate units to be assembled as an appendage. The film-disc transfer panel is an apparatus separately mounted on the wall. The new plan provides that these individual pieces shall join into a single united whole. A pedestal is to be supplied which will have space for placing the driving motor and mounting the disc turntable. The film reproducer and amplifier will form a definite part of the pedestal. A film-disc transfer will be associated with each unit which will permit the projectionist in making his machine ready for the succeeding selection to prepare completely for the change-over. As any equalizers which may be necessary will also be included in the pedestal, special wiring or switching of such units will be eliminated. A mechanical brake will provide ready stopping of the projector. A model of this complete device has been installed in the booth in this auditorium and is being used in the projection of sound pictures.

The installation engineer next turns his attention to the stage. The horns are placed in the mountings which have been constructed by now and are located in positions which experience has taught the engineer may be roughly correct for this type of house. After

the loud speaking receivers are attached to the horns and connected in circuit, a cursory test follows to assure that no major errors are present. This is the first opportunity to produce sound through the complete system. Any imperfections that are immediately obvious are corrected. Comparative tests are then made between the sound reproducers on the projectors equipped, so that variations in volume can be compensated for. Each receiver and horn is heard separately, and then in unison to check poling. Receivers incorrectly poled give a most unpleasant effect of pressure in the ears of the listener if he is at the junction of their sound paths.

Before proceeding further it is desirable to have in place the screen used with the sound system. An obvious requisite of talking pictures is that the sound shall seem to emanate directly from the action shown on the screen. If the sound source is placed immediately behind the area of action in the picture, the illusion is optimum. While it is true that the human mind tends to adjust itself to disregard imperfections in this particular, extensive study has shown that, where the sound originates from locations other than at the visual source of action, an impression of unnaturalness is often present. The auditor is probably not aware of the cause of his uneasiness, but he is unconsciously attempting to convince himself that he is hearing aright. Imperfections of location become less annoying, of course, the farther one is away from the screen. To present the best illusion a special semi-porous screen is used which permits sound from the horns located directly behind it to pass through readily. With the present type in use, a small percentage of light is lost from the picture.

With the screen in place and the horns temporarily set, the acoustic tests can be made and the final check given to the system.

Acoustic conditions of theatres are responsible for widely different results obtained. Some houses give a mellow effect, others make reproduced sounds appear metallic. The shape of the interior has less effect in general than has the nature of the surface of the walls, ceiling and floor. If these surfaces are hard and smooth like ordinary plaster, concrete, polished wood or glass, they will reflect most of the sound striking them. Different frequencies may be reflected in varying proportion. Where surfaces are soft, thick materials such as heavy drapes, carpets, upholstery, or where the audience covers a relatively large space, a goodly portion

of the sound is absorbed. Pilasters, moldings, cornices and such broken surfaces disperse sound waves and tend to damp them out quickly.

The hard or reverberant type of theatre is especially annoying for speech selections since the duration of audibility is so great that a sound will remain to overlap the sound succeeding it. This gives an effect of poor articulation. For music reproduction, however, a reasonable amount of reverberation is acceptable as it tends to give the effect of fullness and roundness. Another variable factor which further complicates the situation is the changing amount of audience which in itself is an excellent absorbent. Theatres which may be entirely too reverberant empty will sometimes give pleasing results when filled. Unfortunately, it is not possible to have a completely filled house at every performance. It will therefore be seen that at best, a compromise must be tolerated.

Reverberation depends upon the rate of decay of sound and is measured by its inverse, the duration of audibility of a sound of known initial intensity. The introduction of highly absorbent material into a room will have greater absorptive effect on the higher frequencies. If the thickness of the material is increased considerably the absorption of the lower tones will be increased while that of the higher frequencies will remain practically intact. Very thin fabrics such as cheese cloth or bunting absorb only extremely high frequencies.

A highly damped auditorium will cause sound to appear to lack brilliance and definition and will have deadness which in extreme cases may be almost depressing. Greater electrical power will be required to fill the house with comfortable sound volume, but the effect of the audience will be relatively less than it is in a reverberant house.

Echoes, generally speaking, are due to too great differences in the lengths of the sound paths of direct and reflected sound which reach an auditor in a given position in a room. An interval of about $1/16$ second is noticeable. Proper location of the source of sound, or placing draping material over the offending reflecting surface will ordinarily correct echo.

Interference is usually produced by the crossing of many trains of sound waves reflected from various parts of the room. It results in distortion and is overcome by proper placing of absorbent.

Resonance occurs with a surface consisting of some thin, hard material which is free to vibrate as a diaphragm at its own natural frequency. Thus sound is reinforced. Distortion will probably result, since only that portion of complex sound whose frequency is near the natural period of the resonator is affected.

Armed with a knowledge of these general acoustic considerations and bearing in mind the three prime requisites to good hearing, i.e., that sound should be sufficiently but not unnaturally loud for all auditors, that successive sounds be clear and distinct, and that the components of complex sound should retain their relative intensities, the engineer makes his acoustic adjustments. He usually tests first for sound distribution and arranges his horns so that in so far as possible all portions of the house receive a like amount. Good distribution can normally be obtained by proper flaring and tilting of the horns. Any acoustic peculiarities are next investigated and where possible corrected. Slight variation in the location of the horns may result in quite marked differences in the results obtained, for which reason this test may involve many hours of labor. It may be necessary to convince the management that acoustic treatment is essential if good reproduction is to be obtained.

One standard practice which is followed in all cases requires that the horns and the back of the screen not occupied by the horns be completely enveloped by absorbent drapes. If the sheet is set back from the proscenium arch, it is also usual to hang drapes in shadow box effect. This treatment eliminates back stage reflections of sound.

After the horn locations have been definitely fixed and the equipment given a final check, the engineer proceeds to calibrate the theatre. He has available several test records embracing a rather wide variety of character of selection to cover various types of entertainment which will be shown in future in the theatre. Each record has been marked with a proper fader setting determined in a standard theatre. By playing these records at the marked value and adjusting the main volume control potentiometer on the amplifying equipment until the proper effects are obtained, it should be possible from then on to obtain good results by using normal fader volumes for any succeeding selections. In other words, this potentiometer setting which then remains fixed compensates for the varying sizes of theatres and permits like effects

of reproduction to be obtained universally. In addition, various types of selection require that varying degrees of volume be fed to the different horns. From the test records the engineer is able definitely to select what these volumes should be and so establish the horn setting values which are normally required. When these potentiometer values and horn settings are determined the theatre is considered calibrated. Such routine tends to standardize sound reproduction in so far as that is possible in theatres using sound projector systems.

While the installation has been progressing the operating personnel have been instructed in regard to the functioning of the equipment and the proper method of handling it. At the outset each man has been given a copy of a complete operating instruction bulletin for his personal keeping for study and reference. By the time of the completion of the work, and as a result of the running of the equipment during the acoustic tests the projectionist should now be able to start up and adjust the amplifying equipment preparatory to running the show. He should be able to thread the projector with film through the sound gate compartment with surety and for film reproduction adjust his sound reproducer lamp. For disc reproduction he should know how to place the starting mark of the film in its aperture and fix the needle of the reproducer on the starting mark of the record.

The rehearsal of the opening program is an important event. It not only enables the projectionists to demonstrate their ability in handling the equipment under real operating conditions, but also gives them experience in actual change-overs of picture and fader. The engineer can acquaint the manager with the technique of running the show to obtain best results. While the physical operation of the apparatus is the responsibility of the projectionist, the manager in the last analysis is responsible for the general effects in the theatre proper. Either he or someone assigned to the work should be present in the audience during the showing of sound pictures. Even though rehearsals of programs have indicated proper operating points of the various selections certain conditions arise which may require changes in volume. The observer is able to be in touch with the projection room for transmitting his wishes by means of a buzzer signal system and telephone circuit, which are provided. It is, of course, essential that this observer not only be entirely familiar with the results which the system may be expected

to give, but should also know how to originate requests for obtaining the changes which he may want. Upon the ability and conscientious effort of this observer depends in a large measure the success of the sound picture programs.

The installation personnel remain at the theatre until it is evident that the equipment can be handled in a commendable manner. At such time the installation is transferred to the service organization of the Electrical Research Products, Inc.

The function of the Service Department is evidenced by its name. The service engineer in whose district the theatre is located is available for emergency calls at all times. In addition, he visits the theatre periodically to check the equipment and recommend what minor adjustments may be necessary. He listens to the selections on the program and makes any suggestion to the manager which may occur to him. In this manner all of the theatre systems are kept under frequent engineering supervision in an earnest endeavor to maintain the class of service which they may be expected to give.

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